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THE LIQUID ROCKET PLANT AT AZUSA

ENGINE OPERATING PROBLEMS IN SPACE
VOL. II—THE SPACE ENVIRONMENT

A REPORT TO
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

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AEROJET-GENERAL CORPORATION



ENGINE OPERATING PROBLEMS IN SPACE.

VOL. II - THE SPACE ENVIRONMENT

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D. Christensen

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FOREWORD

This report, which summarizes the work performed during the first 13 months of NASA Contract NAS7-98, is submitted in partial fulfillment of contract provisions. It was prepared by the Space Propulsion Division of the Liquid Rocket Plant, Azusa, California. The contract was initiated by Dr. Henry Burlage, Chief, Liquid Propulsion Systems, NASA Headquarters, Washington, D. C. The Headquarters Project Manager is Frank Compitello, and the program is under the technical direction of Louis Toth of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif. The work described herein was performed between 15 February 1962 and 14 March 1963.

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INTRODUCTION

Important elements of the planetary and interplanetary environments are discussed in the sections which follow. Our present knowledge of this environment is so quantitatively incomplete, and concepts and ideas develop or change so rapidly, that a description of this environment, as now understood, cannot be presented simply as a collection of formulas, tables, and graphs. Therefore, the description of the space environment is given in the form of a concise discussion combined with tables and graphs showing the test, or otherwise typical, quantitative information. In this way, the most intelligent use of existing data can be made. Before use is made of any particular figure or table, it is recommended that the entire relevant discussion be read.

I. THE SOLAR SYSTEM

The solar system and its neighboring stars travel along a spiral arm of the Milky Way galaxy at a velocity of 300 km/sec in the direction of the star Deneb. The sun and its companions travel in approximately circular orbits, completing one revolution about the galaxy in a period of 2×10^8 years. Since the solar system is 5×10^9 years old, it has made approximately 25 revolutions in its lifetime.

Superimposed on this average stellar motion, the sun is moving 20 km/sec relative to the surrounding stars toward the constellation Hercules. Like most stars, the sun's peculiar motion is much less than the velocity of galactic rotation.

The sun is an average star accompanied by nine planets and many lesser bodies. Since the sun represents 99.2% of the solar system's mass, it dominates the motion of all other objects and occupies a central position in the system. In addition to the sun, the main components are the interplanetary space including gas particles and associated magnetic fields and radiation, the asteroids, meteoroids and comets, and the planets and their satellites.

For convenient reference, various physical and orbital data of the solar system and its components are presented in Tables 1 through 5. Most of this material is from Ehricke (Ref. 20), with certain modifications, particularly with relation to improved physical data of the planets now available, which is discussed in detail in Section II. The orbital data have been calculated with reference to January 1, 1963, as an arbitrarily selected recent date of interest.

Possessing more than 98% of the entire system's angular momentum, the planets extend the domain more than 6000 solar radii. With the exception of Mercury and Pluto, all the planets move in nearly circular orbits about the sun

I The Solar System (cont.)

in a plane very slightly inclined to the sun's equator (Figure 1). Both Mercury and Pluto have relatively large inclinations and eccentricities. Especially pronounced in the case of the latter, its eccentricity permits this remote body to come within the orbit of Neptune while its inclination prevents any possible collision with that planet (see Figure 2).

In trying to draw to scale the distances of the planets from the sun, one finds that the innermost of these bodies are much closer together than their remote counterparts. Indeed, the amount of space between the orbits of the sixth and the seventh planets (Saturn and Uranus) is three times greater than the area occupied by all six inner planets. In 1772 J. E. Bode made an attempt to find a relation which would agree with the known distances of the planets. Taking the earth's distance as unity and using the relation $0.4 + (0.3 \times 2^n)$, he came up with values given in the following tabulation.

Planet	True Distance A.U.	Bode's Relation
Mercury	0.4	$0.4 \times (0.3 \times 2^{-1}) = 0.5$
Venus	0.7	$0.4 \times (0.3 \times 2^0) = 0.7$
Earth	1.0	$0.4 \times (0.3 \times 2^1) = 1.0$
Mars	1.5	$0.4 \times (0.3 \times 2^2) = 1.6$
Asteroids	2.8	$0.4 \times (0.3 \times 2^3) = 2.8$
Jupiter	5.2	$0.4 \times (0.3 \times 2^4) = 5.2$
Saturn	9.5	$0.4 \times (0.3 \times 2^5) = 10.0$
Uranus	19.2	$0.4 \times (0.3 \times 2^6) = 19.6$
Neptune	30.1	$0.4 \times (0.3 \times 2^7) = 38.8$
Pluto	39.5	$0.4 \times (0.3 \times 2^8) = 77.2$

There seems to be no scientific basis for his formula, and although it does not work too well for Neptune and Pluto, it must be remembered that the relation was used before the discovery of Uranus and the minor planets. In fact, Bode's relation stimulated the search for a planet between Mars and Jupiter after the discovery of Uranus yielded a value close to that predicted by Bode. As a result, the asteroids were discovered.

I The Solar System (cont.)

As seen from the north, almost all motions in the solar system are in the counterclockwise direction (direct motion). Because of the different sidereal period for each planet, they are constantly changing position relative to one another. Figures 2 and 3 show, to scale, their relative positions for January 1, 1963.

All the planets revolve and rotate directly, with the exception of Uranus and probably Venus. Uranus is unusual in that its equator is inclined more than ninety degrees to its orbital plane, resulting in a technically retrograde rotation. From recent radar data, Venus is known to have a slow retrograde diurnal motion assuming the axis of rotation is perpendicular to the orbital plane. Whether or not the Venus rotational axis is inclined (making the rotation technically direct) is not yet known because of the thick Venusian atmosphere which obscures the surface.

Though not so opaque as the Venusian clouds, the atmospheres of all the other planets are substantial, again excepting the innermost and outermost planets of the system. Mercury is hot, causing most gases on its surface to boil away, while Pluto's low temperatures freeze out all elements but hydrogen. One other body, Titan, the sixth and largest of Saturn's satellites, possesses a significant atmosphere. In this respect, it is unique among the satellites.

Jupiter, with 12 of the system's 31 satellites, is a solar system in miniature (Figure 4). Varying in size from rocks 8 km in diameter to planetoids as big as Mercury, the satellites revolve about their primaries while following the parent around the sun. As in the case of the planets, most of the satellites revolve directly, except for a few of the outer and less stable bodies. The five satellites of Uranus revolve in the plane of that planet's equator and are technically in retrograde motion due to the unusual inclination of the planet. The rings of Saturn complete the list of features connected with the planets. One of the most beautiful features of the solar system, it is also one of the marvels of nature in that it forms the most perfect plane known to man.

I The Solar System (cont.)

A. THE SUN

The sun, a typical yellow dwarf star of spectral class G2, is the energy source for essentially all the dynamic processes occurring in the solar system (Ref. 1). While the diameter of the sharp observed solar boundary is nearly a million miles (1.4×10^6 km), at the earth-sun distance of 93 million miles the sun subtends an angle of only $1/2^\circ$. From the sun, the earth is a tiny disk of only 17" of arc, or less than 0.005° . Consequently, the earth intercepts only an exceedingly small fraction of the sun's radiant energy. It has been estimated (Ref. 2) that three days of solar flux provide as much energy as could be derived by burning the entire oil, coal, and wood supplies found on earth.

1. Solar Structure

The ultrahigh temperature and pressures of the sun's interior are estimated to be as much as 10 million degrees at 50 million atmospheres (Ref. 3), these values declining rapidly away from the center region. It was formerly believed that the central regions of the sun were dominated by convective processes where the hot gases travelled outward from the center to the cooler periphery. Now it is known that the dominant heat-transfer process in the sun's interior is by radiation. The diameter of the inner core is considered to be about 8×10^6 km, or a little more than half that of the apparent sun diameter. The temperature and density diminish rapidly from the inner core toward the outside, with radiative transfer still dominating this extended core region. Adjacent to the radiative interior is a convective envelope from 140,000 to 200,000 km thick extending to a layer just below the visible surface and containing no more than 2% of the total mass. The estimated temperature gradient (Ref. 1) throughout this inner structure is given in Figure 5.

The outer atmospheres of the sun are classified into three main regions - the photosphere, the chromosphere, and the corona, shown in the following short tabulation. The extremes in thermal environment across these regions are shown in Figure 5.

I The Solar System, A (cont.)

<u>Region</u>	<u>Depth</u>
Core	4,000,000 km
Convective Envelope	200,000 km
Photosphere	600 km
Chromosphere	10,000 km
Corona	60 solar radii

solar "atmosphere"

The distinguishing features of the solar "atmosphere" regions, the photosphere, chromosphere, and corona, are summarized below:

a. The photosphere, or light sphere, is the apparent sun surface, a relatively thin layer (600 km) of highly luminous gas. The gaseous photosphere emits the greater part of the sun's radiant energy at a temperature of $6,000^{\circ}\text{K}$, with a pressure of less than one-hundredth that of the earth's atmosphere. The surface of the photosphere is observed to have a mottled appearance, called "granulation," associated with the convective instability and turbulence of the lower layers. These granules, often 1,000 miles across, appear to move upward at speeds of 1 km/sec. Sunspot disturbances, discussed below, are observed in the photosphere region.

b. The chromosphere, adjacent to the photosphere, is a hazy region 10,000 km thick characterized by irregular, fine, jet-like streaks that shoot upward at velocities of 20 km/sec to heights of 10,000 km. The temperature increases across the chromosphere from $6,000^{\circ}\text{K}$ in the photosphere to 10^6K in the corona.

c. The solar corona, the outermost region of the sun, is a halo of hot, tenuous, ionized gases extending far into the solar system. During an eclipse of the sun by the moon, the solar corona can be observed as far as 20 solar radii. The eclipse of the Crab nebula shows that the corona extends to 60 solar radii. The corona, made visible by the white light from the photosphere scattered by the corona free electrons, is responsible for the emission of solar X-rays.

I The Solar System, A (cont.)

2. Composition

Various chemical compositions for the interior of the sun have been calculated by a number of theories. Some of the predicted compositions (by weight), based on various solar models, are listed below:

<u>Theorist</u>	<u>Composition</u>		
	<u>Hydrogen</u>	<u>Helium</u>	<u>Heavy Elements</u>
Friedman (Ref. 2, 1962)	.60	.29	.11
Kuiper (Ref. 1, 1953)	.76	.23	.0075
Epstein, 1951	.82	.17	.01
Keller, 1948	.67	.29	.045
Schwarzschild, 1946	.47	.41	.12
Bethe, 1939	.35	.00	.65

Sixty-seven elements have been identified spectroscopically in the sun, with 15 known elements missing. Certain elements cannot be identified because of present inadequacies of laboratory equipment; these include Hg, I, Br, Xe, Cl, A, Ne, and others. Conversely, a number of solar lines exist which defy identification. Hydrogen and calcium are predominant elements in the chromosphere. Bright clouds of hydrogen and calcium are also a particular feature of the photosphere over regions containing sunspots.

3. Solar Magnetic Field

The sun has a dipole magnetic field of the order of a few gauss. At the poles, the field is small, having opposite polarity in the northern and southern hemispheres. Near the surface of the sun at sunspots, the local magnetic field intensity is as much as 3,000 gauss and is, therefore, large enough to impart and control the motion of the solar plasma. Further away from the sun in interplanetary space, the situation is reversed with the plasma particles determining the positioning of the magnetic lines of force. The interplanetary magnetic fields are discussed in Section I,C.

I The Solar System, A (cont.)

4. Solar Rotation

The period of rotation of the sun varies from about 24 to 27 days, depending on the latitude, with the period increasing at the poles. The rotation is in the same direction as the orbital motion of the planets and with the same axial rotation of all the planets, except Uranus.

5. Flares and Prominences

While the mass, radius, and luminosity of the sun have not changed appreciably over billions of years, the solar surface exhibits a vast number of transient phenomena. The most obvious disturbance is the sunspot, a cool ($4,500^{\circ}\text{K}$) region visible as a dark spot with dimensions of about 10,000 km. The occurrence of sunspots, generally indicative of solar activity, follows a 22-year cycle.

Associated with sunspots and sunspot groups, the solar flare is by far the most important solar activity insofar as interplanetary travel is concerned. A flare is a bright cloud forming above the photosphere and lasting as long as a half hour. A large flare, $4 \cdot 10^4$ km, may radiate 10^{33} ergs during a 1,000-sec lifetime. Such flares constitute a serious hazard to interplanetary flight and are discussed separately in Section III.

Certain specific active regions of the sun often maintain their identity through several solar rotations (~ 27 days). Careful charting, based on satellite observations, of these activity periods, particularly the flares, is currently in progress.

6. Solar Radiation

The total flux of electromagnetic radiation from the sun is suprisingly constant over a year's time, even during violent disturbances on the sun's surface. The bulk of the energy in the solar spectrum lies between 0.3 and 4.0μ , with approximately 1% of the energy lying beyond these limits.

I The Solar System, A (cont.)

The solar constant, the total solar irradiance at the earth's mean distance (one astronomical unit) from the sun, is given by Johnson (1954, Ref. 4) as $2.0^{\circ} \pm .04$ calories/cm²-min, or $1.4 \cdot 10$ ergs/cm² sec, or about 443 Btu/ft²hour. This figure does not vary by more than 2% during periods of solar activity. The total energy generated by the sun is therefore the area of a sphere of one astronomical unit times the solar constant, or,

$$\begin{aligned}\text{Total energy radiated} &= 4\pi(1.5 \cdot 10^{13})^2 \cdot (1.4) \cdot 10^6 = 4 \cdot 10^{33} \text{ ergs/sec} \\ &= 4 \cdot 10^{26} \text{ watts}\end{aligned}$$

The electromagnetic radiation* of the sun as seen at the earth outside the atmosphere consists of a continuous spectrum in the near-ultraviolet, visible, and infrared regions containing many absorption lines (Fraunhofer lines) and a number of emission lines at shorter wavelengths which contribute only a small amount of energy compared with the continuum. Rocket observations have shown that the continuous spectrum diminishes in intensity very rapidly with decreasing ultraviolet wavelength and that, below 1400 Å, the sun radiates a continuous spectrum with emission lines superimposed upon it. This is unlike the visible and near-ultraviolet, where the continuum is crowded with intense absorption lines and there are no emission lines.

The continuous spectrum can be well approximated in various wavelength intervals by blackbody radiation of a specified temperature. For example, the visible and infrared regions show a spectral irradiance corresponding rather closely to that of a 6000°K blackbody source. The temperature of a blackbody that most nearly matches the continuous spectrum of sunlight in total energy output is about 5750°K. The distribution of energy in sunlight outside the earth's atmosphere is shown in Figure 22. The ultraviolet region where emission lines become prominent is shown in more detail in Figure 23,

*A more complete discussion of solar radiation is presented in a recent survey by N. Williams and D. Christensen (Ref. 5).

I The Solar System, A (cont.)

which is taken from the work of Detwiler, Purcell, and Tousey of N.R.L. (Tousey, 1961, Ref. 7). From 1040 to 912 A, the spectrum consists mostly of emission lines which are not resolved in the plot with 10-A intervals. The extreme ultraviolet shown in this figure originates from higher levels in the sun's atmosphere than does the near-ultraviolet and the visible. The continuum in the ultraviolet region probably comes mainly from the low chromosphere, where the temperature is of the order of 4000-5000°K. The emission lines at short wavelengths originate in still higher regions of the solar atmosphere, where the temperature ranges from 5000°K in the chromosphere to millions of degrees in the corona. The exact region of emission depends on the particular line.

An important series of emission lines is the Lyman series in the hydrogen spectrum, with the first line, Lyman alpha, at 1216 A. The Lyman-alpha line carries about 6 ergs/cm²-sec near solar maximum and delivers more energy than the entire solar spectrum from wavelengths shorter than itself. The intensity is probably less at sunspot minimum. The higher members of the series are followed by the Lyman continuum, which is the most important emission below 912 A. It follows a 6700°K blackbody curve. At 584 and 304 A there are intense emissions by neutral and ionized helium, respectively. The two lines produce on the order of 0.5 erg/cm²-sec at the earth (Hinteregger, 1960, Ref. 8).

A very small portion (~0.1%) of the electromagnetic radiation lies in the soft X-ray region of a few kv. This ionizing radiation is absorbed strongly by materials and does not pose a problem to manned space flight. The radiation hazard is discussed further in Section III.

B. INTERPLANETARY SPACE

The interplanetary medium can be considered as an extension of the sun's corona, with particles and magnetic fields from outside the solar system superimposed. The particles which make up this medium range in energy from a few electron volts to relativistic energies and higher (7×10^{19} ev). The broad range of energies covered by these particles is shown in Figure 6.

I The Solar System, B (cont.)1. Interplanetary Gas

The streams of ionized gas that move outward from the sun extend in a continuously diminishing field to at least as far as the earth's orbit. This gas movement, first deduced from an analysis of motion of comet tails (Ref. 9) has been established directly from satellite measurements (Refs. 10 and 11) and more recently by Mariner II data (Ref. 30). This efflux of gas particles from the sun across planetary space is called the solar wind. (Other particles, notably solar flares and cosmic rays, accelerate along magnetic lines of force through space.)

The velocity of the solar wind, as measured on Mariner II (Ref. 30), varies from 200 to 500 miles/sec, and its temperature is in the neighborhood of 100,000 to a million degrees Fahrenheit with $2 \cdot 10^5$ a reasonable average. Its tenuousness is almost beyond comprehension, there being only 1 to 4 protons (hydrogen nuclei) and electrons per cubic centimeter with 88/cc a maximum (Ref. 30). These Mariner II data (Ref. 30) are compared with observatory (eclipse) and satellite data (Ref. 12) in Figure 7. Note that Mariner temperatures are longitudinal temperatures, not the random temperatures of the various theories summarized in the cross-hatched regions. Therefore whether or not the high Mariner temperatures actually contradict the results of a wide variety of postulated thermal models cannot yet be stated. Further, the Mariner data were found to be both larger and smaller than the Explorer X, with the Mariner providing a vastly larger number of data points in time. The Mariner results therefore represent a better average than the single point location given for example in Ref. 12 and shown for comparison in Fig. 7.

The rate at which these particles move through space (the solar wind) is evidently closely related with the sun's activity. The Mariner results show that on approximately 20 occasions during the flight the solar wind velocity increased within a day or two by amounts from 20 to 100%. These fluctuations correlate very well with the amount of magnetic disturbance observed on earth. This same effect had been observed earlier from satellite data (Refs. 10, 13).

I The Solar System, B (cont.)

Hydrogen particles also occupy interplanetary space with a density of about 500/cc. These particles are luminous because of fluorescence (absorption of ultraviolet sunlight and re-emission of it in the form of Lyman-alpha quanta). It is thought (Ref. 14) that these hydrogen atoms are driven out of the solar system by radiation pressure and are continually being replenished by the sun.

2. Magnetic Fields

The general galactic field is thought to have fields of 10^{-5} to 10^{-6} gauss (Ref. 12). Data from Pioneer V revealed a remarkably stable and uniform (nonradial) interplanetary magnetic-field strength of $2.7 \cdot 10^{-5}$ gauss (Ref. 15). Salisbury (Ref. 12) has suggested that the spatial uniformity indicates the presence of a galactic-interstellar field.

The solar magnetic fields lie superimposed on the general galactic field. One model of the solar field assumes the solar wind to extend the lines of force of the general solar field into a radial configuration. Each line of force is drawn out to a location where, far beyond the earth's orbit, the force lines cross the equatorial plane and return to the opposite hemisphere on the sun. This model has been confirmed by Mariner II data. Another type of solar magnetic field has been proposed which is similar to a long tongue (or magnetic "bottle") extending from the sun's surface (Ref. 16). Although it has been argued (Refs. 17, 18) that a magnetic tongue rooted in the sun's surface is necessary to explain certain cosmic ray phenomena, these arguments no longer appear valid in light of the Mariner results.

Mariner II showed that the field transverse to the radial direction from the sun is typically 2 to 5 gammas at quiet times and has some tendency to have its direction approximately parallel to the plane of the earth's orbit. An appreciable perpendicular component exists much of the time, and fluctuations of 10 to 20 gammas are not uncommon. Such fluctuations usually correlate with changes in the solar wind velocity. (For comparison, the earth's magnetic field is approximately 30,000 gammas at the equator and 50,000 gammas at the poles.)

I The Solar System, B (cont.)

Instabilities and disorders in magnetic field lines can be caused by a number of events, primarily energetic particle motion and field reversal interactions. The region of disordered magnetic fields, thought to lie beyond the earth's orbit, may also produce a clumping of field lines with particles accumulating in the weaker regions.

3. Interplanetary Radiation

Both electromagnetic and corpuscular radiation permeate interplanetary space. This radiation varies both with location and time. The electromagnetic radiations span the entire spectrum from radiowaves to high-energy gamma rays. The energy span for corpuscular radiation (Figure 6) also covers a vast range of energies (Ref. 16). The principal sources of corpuscular radiation are from galactic cosmic rays, trapped electrons and protons, and solar-flare protons. The general topic of interplanetary radiation, extremely important in space travel, is treated at length in Section III.

C. ASTEROIDS

The asteroids, or minor planets, are small planet-like bodies in Keplerian orbits about the sun. They are chiefly concentrated between the orbits of Mars and Jupiter. Their discovery came as a result of searching for a planet 2.8 astronomical units from the sun, as predicted by Bode's relation. This belief in Bode's empirical formula came about when the discovered position of Uranus agreed with the value he had predicted nine years before. Instead of a single planet, many small bodies were detected. Approximately 2,000 have been discovered to date (Ref. 19).

Orbits of all sizes, eccentricities and inclinations can be found among the asteroids, but most lie between 2.1 and 3.5 A.U., near the plane of the ecliptic; all travel in direct motion about the sun. They have average inclinations and eccentricities, of 9.5° and 0.15° respectively, with periods ranging from 3.5 to 6 years (Ref. 14). Some of these orbits are shown in Figure 8.

I The Solar System, C (cont.)

Distribution is not uniform, however. At distances from the sun which are simple fractions of Jupiter's semimajor axis, there are noticeable drops in asteroid density. Known as Kirkwood Gaps, they are produced by Jupiter's repetitive attraction in an outward direction on bodies in this region.

Jupiter in conjunction with the sun also provides two stable Lagrangian libration points in its orbital plane which form equilateral triangles with these two bodies. Twelve asteroids are found at these points, seven to be east of Jupiter and five to the west, each with a period equal to the Jovian year.

Ceres, Pallas, Juno, and Vesta, with a combined mass of one four-thousandth that of the earth, account for 75 to 80% of the total mass of all asteroids (Ref. 20), both known and unknown. Ceres, the largest asteroid, only 770 km in diameter and with a surface gravity of only 0.1 g, could not possibly hold a significant atmosphere (Ref. 21).

Since the minor planets are too small to visually determine the size of their disks, their diameters are computed by measuring their brightness. Assuming that their reflecting power is about equal to that of the moon, it can be shown (Ref. 22) that

$$\log d = 3.13 + \log a (a-1) - .012 m + 11 c$$

where d = diameter in km.

a = distance from the sun at opposition in A.U.

m = visual stellar magnitude at opposition

c = variation of brightness in magnitudes per degree phase

Although there must be many small asteroids, those which have been discovered are fairly sizeable. Of the 27 known asteroids which cross the Martian orbit, two-thirds exceed 10 km in diameter (Ref. 23).

I The Solar System, C (cont.)

The albedos of the asteroids are highly variable; Vesta is especially bright, reflecting 55% of the sun's light (Ref. 24). This leads to the speculation that it has a snow covering. Traces of the heavier gases may be the cause of the high albedos on some of the larger asteroids. A few show large fluctuations in brightness which are due to rotation of their non-spherical shape. One is believed to have the shape of a dumbbell. The periods of rotation are all small, none being greater than 10 hours.

Among the great number of known asteroids, a few are of special interest. Hidalgo has both the highest eccentricity (0.6557) and the greatest inclination (42.529°) of any known minor planet (Ref. 20). Geographos has the distinction of making the closest predictable approach to the earth's orbit and will come within three million miles of the earth in the near future. One of the most interesting and unusual asteroids, Icarus, is the only body other than comets and meteors which passes within the orbit of Mercury (0.1869 A.U.) at its closest approach to the sun (see Fig. 8). Its surface, alternately exposed to the extremes of heat and cold, must be unique in the solar system.

Asteroids will not be explored in the near future, however, since their high inclinations to the ecliptic require large amounts of energy to land a vehicle on one of these bodies. The planets will have priority as well as lower energy requirements, resulting in a much delayed exploration of most asteroids. A study of the surface of Icarus would be especially interesting, but again, as with the other asteroids, it is highly inclined to the ecliptic, making transfer difficult. In 1968 a vehicle could be sent the four million miles to this asteroid on a minimum energy orbit, but the people would have to gather its data rapidly as its velocity relative to Icarus would not allow a very long observation time.

Eventually the larger asteroids will be explored, but their value at the present time is questionable. Contrary to some popular thinking, the asteroids will not provide rides for vehicles to other planets (Ref. 20) nor will they be a great menace to vehicles traveling through the asteroid belt.

I The Solar System, C (cont.)

Even a million asteroids could not clutter the space between the Jovian and Martian orbits (Ref. 21). However, a concentration of meteoritic matter in the asteroid belt is probable and would present a appreciable hazard.

D. METEORIODS AND COMETS

Interplanetary space contains many small particles about the size of sand grains traveling in elliptical orbits around the sun. These and their larger but rarer cousins are classified as meteoroids.

The term "meteorite" is used only for those remnants of meteoroids found on the earth's surface which are not completely burned up upon entry into the atmosphere. Each year the earth collects about 2×10^9 kg of meteorites of all sizes (Ref. 14). Although large meteorites are rare, a few have been found which are greater than 10,000 kg. Craters left by meteorites on the order of 10^6 kilograms, such as the Barringer crater in Arizona, must have been produced by bodies which were of asteroidal dimensions prior to atmospheric ablation (Ref. 25).

Observations of meteors as they enter the atmosphere reveal that most if not all meteors travel with a velocity of less than 42 km/sec as the earth's orbit and are therefore part of the solar system (Ref. 20). A few have been observed which exceed this value, but it is more likely that they obtained their hyperbolic orbits from perturbations of the planets rather than from being true interstellar bodies. Unlike the asteroids, not all meteors travel in direct motion about the sun. Many meteors have been recorded entering the atmosphere at 72 km/sec opposite from the direction of the earth's motion. This is caused by the earth's 30 km/sec velocity about the sun.

Meteorites of two different compositions have been found - the stony and the iron types. Both are believed to have a similar origin as their rough surface seems to indicate that they are formed by a collision process. Sporadic, in contrast to the regularly occurring meteor showers, this type in all probability has originated from constant collisions among the asteroids

I The Solar System, D (cont.)

and is part of these bodies. In explaining the two different compositions, it is thought by some that the iron meteoroids come from the core of a once single planet between Mars and Jupiter and that the stony meteoroids once formed its outer crust. Many fine dust particles of interplanetary space also seem to be asteroidal in origin. After collision, the resulting dust escapes easily from the low-mass parent bodies and accumulates in a heavy concentration near the sun and similarly in a ring-like area in the asteroid belt near the plane of the ecliptic (Ref. 14). Many of the finer particles are kept in equilibrium by the balancing of radiation pressure and solar gravitation (Poynting-Robertson effect).

Unlike sporadic meteoroids, shower meteoroids of cometary origin travel in groups which follow the same orbit and have the same periods. They appear and reappear in the vicinity of the earth at predictable times in association with a comet from which they originated (Ref. 25). No meteorite of the cometary type has ever been found, but spectra of these particles indicate a stony composition. In contrast to the rough surfaces of the asteroidal meteoroids, cometary meteoroids are believed to be smooth and spherical in shape, in conformance with the theoretical composition of the comets.

Eight of the known meteor showers have been definitely identified with comets and are noted in the following table (Ref. 12).

<u>Meteor Shower</u>	<u>Comet</u>	<u>Time of Year</u>
Lyrids	Comet 1861 I	April 21
Eta Aquarids	Halley's Comet	May 5
Perseids	Comet 1862 III	August 12
Giacobinids	Comet Giacobini-Zinner	October 9
Orionids	Halley's Comet	October 20
Taurids	Encke's Comet	November 7
Leonids	Comet 1866 I	November 15
Bielids	Biela's Comet	November 23

The shower is usually named after the constellation of stars from which it appears to come (the radiant of the shower).

I The Solar System, D (cont.)

Comets, although seldom seen, are a part of the solar system. Their orbits around the sun are of two types, depending on their past history. Originally, all comets were long-period in type, that is their eccentricities were greater than 0.99 and less than 1. Moving in these extended ellipses with periods ranging from 10^3 to 10^6 years, they would be fairly frequently perturbed sufficiently by one of the larger planets either to completely remove it from the solar system ($e > 1$) or lower its eccentricity, giving it a period comparable to that of the planets (see Fig. 9). Thus, over the millenia, a considerable number of short-period comets have accumulated within the orbit of Pluto. The following table lists the distinguishing features of each type for comparison.

Short Period	Long Period
Period 3 to 165 years	Period 10^3 to 10^6 years
$e = 0.4$ to 0.9	$e = 0.99$
Elliptical orbits	Nearly parabolic orbits
Lie near plane of ecliptic	Concentrated at inclinations of 80 to 150°
Grouped in families associated with the larger planets	No definite grouping
Usually direct motion	Random distribution between direct and retrograde motion

Since short-period comets are captured by a planet, the resulting new orbits are characterized by an aphelion distance about equal to the semimajor axis of the captor. This brings about a grouping of the short-period comets into families associated with each of the larger planets. Jupiter, because of its large mass, has captured more than forty comets, with Saturn, Uranus, and Neptune having considerably fewer. Table 6 gives a partial list of the comets in the various families.

In appearance, a comet differs radically from all other bodies in the solar system. It is composed of three parts - the nucleus, the coma, and the tail. The nucleus is small and round, with a diameter on the order of 1 km.

I The Solar System, D (cont.)

Although small in size, it is very dense, as the average mass varies anywhere from 6×10^{12} to 6×10^{16} tons (Ref. 20). Surrounding the nucleus is a gaseous hull known as the coma, with a density less than a good earth vacuum. This mass of gas contains molecules and atoms liberated by the nucleus and usually consists of OH, NH, CH, CN or C_2 . The tail contains molecules of N_2 , CO, and CO_2 which have been driven away from the sun by radiation pressure. At times the tail attains lengths of hundreds of millions of miles, but it usually does not appear until it is within the orbit of Jupiter.

It has been proposed by Whipple that the nucleus is an icy conglomerate of compounds of nitrogen, oxygen, carbon, and hydrogen, with imbedded silicates and metals (Ref. 26). As the comet approaches the sun, the ice evaporates, resulting in gases which form the coma and tail. This model is the one most generally accepted. Recently Robey has proposed the addition of a permanent coma in the form of a magnetized plasma to account for observed excess light emissions, explosive outbursts, and contraction and expansion of the coma (Ref. 27).

The vaporization of a comet takes place on its nucleus surface and is a process of melting, boiling, and surface microexplosions which disperse solid surface material. At first these particles form a compact cloud which travels in the same orbit as does the nucleus of the comet. With the elapse of time, radiation pressure (Poynting-Robertson effect), solar wind, and perturbations by planets tend to spread the cloud into a large swarm of meteoroids. These swarms of meteoroids are termed meteoroid showers (upon atmospheric entry) and their common orbital path is similar to that of their parent comet. The effect of this orbital attenuation is to cause these particles to spiral into the sun. This process takes an enormous amount of time. During the process each meteoroid is dispersed from its cloud to such an extent that it can no longer be associated with the cloud. Thus the birth of sporadic meteoroids of cometary origin, with a unique orbital path for each particle.

I The Solar System, D (cont.)

Although meteor showers are noted for greatly increased counting rate, the average contribution per annum is only 20 to 30% of the total mass accumulated by Earth (Ref. 28). It is believed that 90% or more of all meteors are of cometary origin (Ref. 29).

The probability of a space vehicle hitting the nucleus of comet is extremely small; however, the gases of the coma and tail occupy a considerably larger volume. Ehricke has shown (Ref. 20) that traveling through such a tenuous gas for a long period could critically alter a vehicle's velocity. Since most of the comets travel in inclined orbits, however, the probability is low that planetary probes would encounter such difficulties.

The most serious danger present to space vehicles by space debris is that which is presented by micrometeoroids. Micrometeoroids are small (0 to 300 μ in diameter) particles in space with masses between 10^{-4} and 10^{-12} . The danger of these particles lies in their much greater frequency than heavier particles and their hypervelocity impact (36,000 to 246,000 ft/sec) on space vehicles.

In order to protect against the micrometeoroid hazard, it is necessary to know the frequency of collisions expected, the characteristics (mass, size and velocity) of the particles encountered, and the characteristics of a micrometeoroid hypervelocity impact (penetration depth, crater size, etc.) These topics are discussed further in Section III.

II. PLANETS AND THEIR SATELLITES

Excessive energy requirements prevent exploration in the near future of any but the nearest planets. Exceedingly long times required for the more remote planets are shown in Figure 10. Travel time required to a given planet on the indicated curve assumes a minimum-energy trajectory as indicated by the top curve. If more energy is available, i.e., the energy lies somewhere in the upper shaded region, then a shorter flight time is obtained, falling in the lower shaded region (Ref. 31).

Clearly, Jupiter's orbit represents the most optimistic goal for inter-planetary travel, at least for the next few years. Therefore, this study emphasizes those planets, namely Mars, Venus and Jupiter, which could be visited within the foreseeable future. However, consideration of the more remote planets is also important since frequently information pertaining to a particular planet is helpful in understanding observations from another. Each of the planets is therefore individually discussed.

Tabulations of the physical and orbital data of the planets and their satellites were presented in Tables 1 through 4. Note that the orbits of the planets, as well as the orbits of the satellites, are nearly circular, and that most of the orbits are nearly coplanar. All of the planets (except Uranus and possibly Venus) and the sun rotate in the same direction in which they revolve. Similarly, most of the satellites and the rings of Saturn revolve around their parent planets in the same direction in which the planets revolve around the sun.

According to their physical characteristics, the nine planets fall into separate groups - terrestrial (resembling the earth), and Jovian, or giant (resembling Jupiter). Although Mercury and Pluto are the extreme opposites on the temperature scale according to their relative distance from the sun (Figure 11) they are similar in that both have small diameters, high densities, low masses, and long rotational periods characteristic of the earth. Thus,

II Planets and Their Satellites (cont.)

together with Mars and Venus, they are termed terrestrial planets. In contrast, Saturn, Uranus, and Neptune are referred to as Jovian or giant planets because of their similarity to Jupiter. Their very low densities, rapid rotation, hydrogen-compound atmospheres, and huge diameters suggest an evolution different from that of the earth. Important features of the planets pertinent to space-propulsion considerations are presented in the sequence as their distance from the sun.

A. MERCURY

Mercury is the smallest of the nine planets, with a diameter of 5000 km. Named Mercury by the Romans, owing to the fact that it speeds faster in its orbit than any other planet (29.8 miles/sec), it is not much larger than the moon and is slightly smaller than the two largest satellites of Jupiter. Its density, however (0.9 of the earth's), more than twice that of Ganymede, is of planetary dimensions.

As a result of being so close to the sun, it has been constrained to rotate and revolve in the same period of 88 days, just as the moon keeps the same face to earth. Nevertheless, only 30% of the planet is in continual total darkness (Ref. 31), since the ellipticity of its orbit ($e = 0.2$) causes rather large librations.

1. Atmosphere

Lyot's polarization curve of Mercury shows an excess of polarization at the cusps, probably indicating the presence of a weak atmosphere (Ref. 32). If it consisted of air, it would have a thickness of only 25 meters and a surface pressure of 1 millibar. The presence of tenuous dust clouds could account for regional departures in the observed polarization curve. Assuming that the gases of this atmosphere were produced after the planet cooled to its present temperature, its most likely constituents are carbon dioxide, oxygen, sulfur dioxide, and argon (Ref. 33). Lighter gases would have long since escaped.

II Planets and Their Satellites, A (cont.)

2. Temperature

Mercury has the most extreme temperatures of any planet in the solar system. At the subsolar point, the temperature varies from 688°K at perihelion to 558°K at aphelion (Ref. 32), as calculated from its blackbody curve and the solar constant. On the dark side, the temperature approaches absolute zero. Because of the large librations, there is a fairly wide belt near the terminator with earthlike temperatures. Only in this twilight zone would surface landings be feasible.

3. Surface

In appearance, Mercury's surface is similar to that of our own moon (Ref. 34). The albedos and polarization curves of both bodies are remarkably alike. Moreover, the increase in the brightness of Mercury from quarter to full phase produced by the disappearance of shadows indicates that the topography of Mercury is at least as mountainous as that of the moon. In the temperature belt mentioned above, libration will produce a "day and night," causing the surface to be alternately heated and cooled. The surface in this area, therefore, is very probably cracked in many places. These natural crevices and the shadows of the mountains could be used to protect an outpost or probe from the heat of the sun when observing that body from the hot side of Mercury (Ref. 32).

Mercury can provide an excellent platform for extended close observation of the sun. Thermal stresses on any package can be greatly reduced by making use of the twilight zone.

B. VENUS

Although Venus is the closest planet to earth, and very similar to earth in its mass and radius, earth-based observations have been hampered by the extremely thick cloud layer covering Venus and the distance separating the two planets. At the closest point to earth, inferior conjunction, Venus is some 26 million miles from earth.

II Planets and Their Satellites, B (cont.)

At the time of the Venus flyby, on 14 December 1962, the Mariner II spacecraft was only 21,000 miles from Venus, permitting close observation of the planet for 35 min. These Mariner II data, together with recent radar and spectroscopic studies, have resolved several controversies concerning the physical properties of the planet. While several important considerations are not yet well understood, such as the circulation, meteorology, and rotation aspects, a good deal is now known, allowing at least the general features of the environment to be described in a realistic way. The following discussion endeavors to concentrate on the most recent concepts rather than elaborate on older formulations which are covered to some extent in the annotated bibliography (primarily Refs. 50 to 100).

1. Physical Properties

The mass, diameter (with cloud cover), and volume were known fairly well prior to the Mariner flight. Since Venus does not have a satellite, the mass had been calculated using the perturbations of the orbits of other planets (Mars and the earth). This procedure, using data collected for decades, has a probable error of 0.05%. From Mariner tracking data, it will be possible to establish the Venus mass within 0.005%.

The rotation period of Venus is believed to be 230 days (± 40 to 50 days) retrograde, based on 1962 radar experiments (Ref. 30). The figure of 225 days retrograde would be defined as a nonrotating Venus, which would keep the same face to the sun at all times. The fact that the rotation is very slow is confirmed by at least four different measurements: Doppler smearing, signal-strength variation with time, Doppler shifts from several range "slices" of the planet, and watching a bright reflecting spot moving across the face of the planet.

The conclusion that the rotation is retrograde is however based on the assumption that the axis of rotation is perpendicular to the radar line of sight from the earth (or nearly perpendicular to the orbital plane). Kopal (Ref. 35) warns that even a 30 or 40° inclination would change the

II Planets and Their Satellites, B (cont.)

interpretation from direct to retrograde. Consequently, statements as to whether the motion is direct or retrograde cannot be made until estimates of the angle of inclination are known. Further, some care should be used in applying the 230-day period, since it is conceivable that libration or wobble of the planet could seriously confuse the observed data. Improved experimental techniques should result in data of higher certainty in 1963.

It is possible that lightning and other atmospheric disturbances occur on Venus. Kraus studied radio signals at 11 cm and concluded that lightning could have produced the observed intensities. More recently, he re-examined the data (1960, Ref. 77) and concluded that the quasi-coherent radiation did not come from Venus but from interference of terrestrial origin. Recent observations by Carr et al. (1961, Ref. 67) failed to show any such disturbances over a 330-hour period of continuous monitoring.

2. Albedo

Evidently, the planet reflects the greater part of the incident solar radiation in the visible region and a much smaller fraction in the violet and near ultraviolet. The albedo of Venus has been measured to be between 0.55 and 0.90 in the visible and infrared and varies markedly with wavelength. Kuiper (1957, Ref. 90) has estimated the effective albedo as 0.67 ± 0.03 . Kuiper's value is probably the most accurate, since the wavelength for which it was determined (5500 Å) is representative of the peak radiant energy of the sun.

3. Surface Characteristics

Almost nothing is known about the structural surface characteristics of Venus. The high surface temperatures measured by Mariner II (700°K , discussed under 6 below), higher than the melting point of lead, confirms the absence of any life as known on earth. It has been inferred from radar data that the surface characteristics may be very similar to those of the earth (Ref. 54). The surface was shown to be rough by cross polarization measurements (Ref. 30) with the average dielectric constant of the surface material similar to that of dust or sand. No indication of major volcanic activity has ever been observed.

II Planets and Their Satellites, B (cont.)

4. Clouds

A yellow cloud cover, fluctuating in optical depth in place and time obscures the solid surface. The nature of these clouds is still disputed among authorities. Sagan (Ref. 74) proposes that the clouds are ice crystals, while Öpik (Ref. 69) suggests they are dust stirred up by strong surface winds. More recently, Kaplan (1963) has suggested hydrocarbons similar to smog (Ref. 41).

The preponderance of physical evidence favors the ice crystal or water vapor theory. Kopal (Ref. 35) recently suggested this viewpoint, mentioning the probability of dust particles at the lower cloud layers. Evans (Ref. 38) also arrived at the water-vaporcloud conclusion by a detailed study of the variation of albedo of Venus with wavelength. While the variation of frequency with wavelength, reported by Evans (Ref. 38) and attributed to Sinton, differs somewhat from Sinton's original measurements (Ref. 36), and while Sinton's measurements cannot be satisfied completely on the basis of a water vapor assumption, many similarities between water vapor cloud absorption (e.g. Hewson, Ref. 44 and Moreland, Ref. 45) are apparent.

From Mariner II data, it is estimated that the cloud layer is 15 to 20 miles thick, with a ceiling of about 45 miles. The temperature is about $+200^{\circ}\text{F}$ at the bottom decreasing to about -30°F , somewhere in the middle of the cloud layer. However, the probe found no evidence of breaks in the clouds as were previously thought to exist because of observed shifting, irregular markings observed from earth. One cold spot in the cloud layer, at least 20° cooler than the surrounding clouds was found indicating a region of higher clouds, or a more opaque area, or both. Temperatures in the cloud layer were found to be the same on the dark side as on the light side.

These Mariner data are in reasonable agreement with observational data as far as comparisons can be made. Spectroscopic temperatures of 300°K (80°F) have been reported by Chamberlain and Kniper (1956, Ref. 94) and others. Spinrad (1962, Ref. 50) calculated a rotational value of 240°K from CO_2 spectra;

II Planets and Their Satellites, B (cont.)

a thermal emission temperature of 234°K in the cloud layer was found by Strong and Sinton (1960, Ref. 71). These correspond roughly to the 200°F to -30°F range measured by Mariner II.

Temperature calculations of $207 - 215^{\circ}\text{K}$ have been computed from the occultation of Regulus (Ref. 39a), data which is usually taken to be about 50 km above the cloud layer.

Although the corresponding pressures can usually be determined by line-broadening from the spectra, the major difficulty, for the purposes of calculating model atmospheres, is in determining corresponding elevations.

5. Atmospheric Constituents

Until 1954, CO_2 was the only known specific molecule present in the Venusian atmosphere (Dunham, 1952, Ref. 100). Molecular nitrogen and other molecules were identified by Kozyrev (1954, Ref. 98). Until recently, CO_2 was thought to be the major constituent. Kopal (Ref. 70) suggested in 1960 that CO_2 was probably only a small part of the atmosphere and that molecular nitrogen formed the major portion. Recently, these ideas were verified by Spinrad (1962, Ref. 50).

Spinrad studied the ten best Mt. Wilson plates and by careful analysis found the total pressures in the atmosphere to be substantially higher than previously computed. The percentage of CO_2 is therefore substantially reduced (to about 5% with an uncertainty factor of 2) making CO_2 only a minor constituent of the atmosphere. In the absence of positive spectroscopic identification, the major constituent creating the high total pressures must therefore be a gas whose emission lines are absorbed in the earth's atmosphere. Nitrogen would appear to be the possible answer.

Spinrad calculated the CO_2 absorption to originate in a region where

$$T_{\text{rot}} = 440^{\circ}\text{K} \text{ with } P \sim 5 \text{ atm.}$$

II Planets and Their Satellites, B (cont.)

Mariner II data failed to show the presence of either water vapor or CO₂, the concentrations being too small to be detected with the probe instrumentation. Evidences of water vapor have been found by Sinton and Strong (1960, Ref. 73), although there are questions to the accuracy due to the uncertainties in the amount of water vapor present in the earth's atmosphere.

6. Thermal Structure of the Venus Atmosphere

The temperature of the Venus atmosphere varies over extreme ranges with height but does not vary appreciably with longitude or latitude location, the temperatures at any given height being similar whether on the sunlit or dark sides of the planet (Mariner II, Ref. 30).

Even before the Mariner II data was available, it had been established from radio signals that the surface temperature was high, (about 600°K) by Mayer, McCullough, and Cloanaker (1958, Ref. 87), and more recently by Lilley (1961, Ref. 63). A radiometric temperature of 700°K ± 140° is usually quoted (Drake, 1962, Ref. 6). The average of this value is identical to the Mariner II measurement.

Kaplan (Dec. 1962, Ref. 56) calculated a "standard" and an extreme model atmosphere for Venus presenting the temperature, density and pressure as functions of height as shown in Fig. 12. Kaplan's model correlates Spinrad's analysis of the old Venus CO₂ spectra with the occultation of Regulus data and radiometric data (8-13μ). The "standard" surface temperature was taken as 700°K, at that time based on radar results but since verified by Mariner II.

Kaplan's calculation was based on the familiar hydrostatic equation of state taking into account the variation of the acceleration of gravity, taken as 900 cm/sec at the surface. Between the significant levels the pressure-temperature relation was assumed to be

$$T_1/T_2 = (P_1/P_2)^k$$

where k was assumed to be constant for each layer (Table 7).

II Planets and Their Satellites, B (cont.)

The results of Kaplan's work are contained in Table 7 and in Figure 12. The standard model is considered adequate for re-entry heating calculations. The curves should not be used to determine flight time between re-entry and ground contact owing to current uncertainties in pressure variation near the surface. However, the high surface temperatures make this limitation of little practical importance.

7. Physical Mechanisms of the Thermal Environment

The description of the Venus atmosphere presented above were attempts to assemble in a systematic way the various observed parameters without investigating actual physical mechanisms which could produce these parameters. In light of Mariner II data, it appears reasonable to construct at least a rudimentary model of the Venusian thermal processes. The now-familiar schematic diagram of the thermal environment is shown in Figure 13. In this model, the incident visible and infrared sunlight permeates the clouds but the resulting thermal emission from the surface is blocked by the cloud layer. Quite probably strong convective currents dominate surface environment, equilibrating the surface temperature around the planet. This process of heating the dark side would be aided by the complete cover of the insulating cloud layer.

The above description would appear to be a combination, with certain modifications, of two well-known theories: the greenhouse model and the aeolosphere model.

The greenhouse model (Sagan, 1960, Ref. 74) explains the high surface temperatures by assuming that the cloud layer, composed of CO_2 and H_2O , is transparent to the incident sunlight in the visible and infrared, but opaque to the far-infrared (thermal) emission from the surface. A sketch of this effect is shown in Figure 14. Verification of the presence of water vapor was found by Strong and Sinton (1960, Ref. 73) although the amount was not established. The calculated values of cloud-layer depth, temperature rise, etc. necessary to support this theory are found to be consistent with observations.

There is disagreement between the calculations of Sagan and Öpik (1956, Ref. 92) regarding the amount of water vapor necessary to support

II Planets and Their Satellites, B (cont.)

the greenhouse effect. Until better measurements are available (Sinton's observed 2×10^{-3} g/cm⁻² of water vapor is in question), the problem cannot be resolved. Spinrad (1962, Ref. 52), by calculating Doppler shift calculations on Dunham's Mt. Wilson plates, has recently confirmed the belief that the water vapor is far less than that reported by Sinton.

The expected surface of Venus, consistent with the greenhouse model, would be dry, calm, overcast, and very hot, with the sun visible through high cirrus clouds.

The aeolosphere model, suggested by Opik (1961, Ref. 69) suggests that the clouds are composed of dust which is stirred up by winds. The surface is, therefore, a perpetual dust storm, with no sunlight but intense heat resulting from the imposed adiabatic heat lapse rate through the stirred up atmosphere. A schematic sketch of the proposed aeolosphere is shown in Figure 15. This theory has been challenged on several points, including possible inconsistencies in the albedo and phase variation of the microwave emission.

Kopal (Ref. 35) has suggested the actual situation may consist of a greenhouse effect in the cloud layer, much as Sagan (Ref. 74) described the mechanism but with the atmosphere under the cloud layer consisting of an aeolosphere as Opik (Ref. 69) described, with hot, perpetual dust storms.

8. Magnetic Fields and Radiation

The Mariner II probe magnetometer did not detect the presence of a magnetic-field (within the 5-gamma limit of sensitivity). At the 21,000 mile altitude above Venus, the magnetic field would have been about 100 to 200 gammas if the Venus magnetic field were similar to that of the earth. These data tend to confirm the theory that the strength of the magnetic field is related to the rate of rotation. Since other experiments have shown that Venus rotates very slowly, if at all, Venus might therefore be expected to have a small magnetic field. It is of course possible that Venus might have a complicated magnetic field structure which would produce high magnetic field intensities locally on the surface without being apparent at the 21,000-mile fly-by distance.

II Planets and Their Satellites, B (cont.)

With regard to theoretical efforts, Kopal had previously pointed out (1960, Ref. 70) that since Venus is approximately the same size and density of the earth, Venus could reasonably be expected to have a similar core and a similar field, and quoting the results of Houtgast (Nature, 1956) shows a 1- to 2-gauss field likely. Recently, however, Kopal (Ref. 35) expressed the view that the magnetic field strength was related to the rotation speed; this would greatly reduce the probability of a Venusian magnetic field. Naroyana (1959, Ref. 83) calculated a 0.4 gauss field, based on statistical plots of daily planetary amplitude. The most recently accepted thesis appears to be that expressed by Newburn (1962, Ref. 56), that the field is much less than that of the earth and is very unlikely to be more than a few gauss.

C. THE EARTH-MOON SYSTEM

The earth's moon is the largest of all moons in relation to the parent planet. Several moons are actually larger, such as Ganymede. Ganymede, however, is only $1/28$ the size of Jupiter, while the earth's moon is $1/4$ the earth's size. This fortuitous situation provides an excellent training ground for practicing the techniques of space flight necessary for exploring the solar system.

Although the nature of the lunar surface has been described in many places [see for example; Fielder, (1961, Ref. 113); Kopal (1960, Ref. 114); and Buwalda, (1960, Ref. 115)], a new evaluation of some of the experimental results is in order for this report since the application of the results will be new. This report is particularly concerned with the influence of lunar environmental conditions on propulsion systems.

The environment encountered by a propulsion system in the neighborhood of the moon is similar to that in interplanetary space with a few important exceptions. Thermal, gravity, and radiation conditions differ from those found in space. Magnetic electric, and gravity fields differ and the density of charged and neutral particles, including meteors, is probably not the same as that in

II Planets and Their Satellites, C (cont.)

space. Dust may be stirred up from the moon's surface and interfere with operations on the surface. On the other hand, presence of solid materials and resources may prove to be advantageous to these operations.

As a first step in describing the lunar environment, a few important constants should be listed to provide a frame of reference for the discussion. The constants are shown in Table 8.

As the table shows, the moon's albedo is low. Only 7% of the sunlight received is reflected. The rest is absorbed. The moon itself radiates heat, known as planetary heat. From this radiated heat the temperature of the surface and of deeper layers may be inferred. Infrared measurements yield the surface temperature which ranges from 400°K at the subsolar point (the point on the moon's surface directly below the sun at any instant) to below 120°K in the shade. This temperature range, from above boiling water, down to nearly liquid-air temperature, is tremendous. Materials and systems will not survive and operate properly under these conditions unless specially designed or thermally protected.

The problem of thermal control is different on the lunar surface than in space. Instead of radiating to cold outer space and receiving essentially no heat in return, a device on or near the moon receives radiation from the moon. It is exposed to cold outer space over only about a hemisphere. The device may be shaded by the moon from solar radiation, and, alternatively, may shade from the sun a small area of the moon's surface, changing its surface temperature. Maintaining the temperature of the device on the moon's surface within a reasonable range may require even more ingenuity than does thermal control in space.

In contrast to the extremes of temperature encountered on the lunar surface, the temperature a short distance below the surface - a foot or two - remains nearly constant at a temperature a little below that of freezing water. (This result was obtained by studying the radio microwave radiation from the lunar surface.) The surface temperature changes because the moon rotates with respect to the sun although it continually keeps one face toward the earth as

II Planets and Their Satellites, C (cont.)

it revolves in its orbit. A point on the moon's surface is sunlit for half a month (one month equals 27.32 days, as shown in Table 11) and shaded for the other half-month. The surface temperature drops rapidly as the area passes into shade, while the temperature of layers below the surface changes slowly. Even more striking, the surface temperature during an eclipse almost directly follows the insolation, while the deeper temperatures lag severely. These results have important bearing on the nature of the surface materials. An extremely low thermal conductivity is indicated for the surface layer. In fact, the indicated thermal conductivity is so low that only fine powders in vacuum can be considered as surface materials. These results apparently demonstrate that there is fine dust over much of the moon's surface, but they also indicate that the dust layer probably isn't very thick, probably less than an inch or a few inches thick. Other lines of evidence support this estimate of thickness although claims have been made for much greater thicknesses. The heat capacity of the surface layer is probably low, while that of material lying below the surface is closer to the heat capacity of common terrestrial rocks. All of these results have bearing on the thermal design of a device for use on the moon.

Radiation other than thermal will offer problems for lunar operations. The ultraviolet, X- and gamma-radiation from the sun will damage some materials if exposure to these rays is sufficiently long. The radiations are exactly the same as those measured in nearby space and for that reason will not be discussed in this section. All of the electromagnetic radiation from the sun travels in straight lines and will fall upon the sunlit side of the moon and not on the dark side.

Charged-particle flux, on the other hand, does not necessarily travel in straight lines, but may be deflected by magnetic or electric fields, and hence presents an extremely complex problem. Solar-flare flux of high-energy particles is particularly complex and is of great concern, since it may damage such materials as solid propellants, electronic components, and plastics. The nature of these solar-flare fluxes will be discussed elsewhere, but it should be pointed out here that many of these particles may reach the side of

II Planets and Their Satellites, C (cont.)

the moon away from the sun. There is no real assurance that hiding from sunlight will enable one to escape solar-flare particles. Charged particle streams from the sun, including the solar wind (which probably "blows" rather gently most of the time) and particle streams from flares, have many other effects. They may affect the charge on the moon's surface or on a vehicle and influence electric fields in the neighborhood of a vehicle. (Photoelectrons generated by ultraviolet light will also contribute to the charge conditions.)

Dust and meteor flux will be important to systems operating on the moon. The flux will resemble that in interplanetary space in the neighborhood of the earth's orbit and will be little influenced by the moon's gravitational field. However, the flux may vary with position on the moon's surface since the flux is not isotropic neither for the moon nor earth. Detailed discussion of the fluxes, masses, and expected damage will not be repeated here since these subjects are covered in the description of the interplanetary environment.

Another important environmental feature is the atmosphere. Almost all attempts to measure any atmosphere near the moon's surface have failed. In fact, Dollfus (1956, Ref. 118), using refined techniques, found that the density of the atmosphere at the surface of the moon must be less than 10^{-9} of the density of the earth's atmosphere at sea level. Elsmore and Whitfield (1955, Ref. 119) detected the presence of a tenuous atmosphere of charged particles by observing occultation of radio stars. Elsmore (1957, Ref. 116) estimated the surface density of electrons to be 10^3 particles per cc and the total density of the atmosphere at the surface of the moon to be less than 6×10^{-12} of terrestrial sea level density. The gases present in minute quantities in the atmosphere may be heavy gases, such as Kr and Xe, or there may be some light gases, temporary visitors from the sun, just as there are throughout interplanetary space, or there may even be a little water vapor (Watson, Murray, and Brown, 1961). In any case, the atmosphere is extremely rarefied and represents a vacuum better than a laboratory high vacuum. High vacuum introduces difficult and challenging materials problems. Many plastics, for example, are useless for vacuum applications. Thermal control paints, electronic potting compounds, lubricants, and

II Planets and Their Satellites, C (cont.)

seals must all be studied carefully for they are likely to be altered by the vacuum and environment and fail to perform their tasks satisfactorily.

Gravity on the moon is one-sixth that on the earth; this will influence mechanical design on some systems, although the changes introduced will not be drastic. Suspension systems, for example, that balance a spring force against a weight force will require design different from that on earth.

The magnetic field of the moon, which may be important in some control units, is very small if it exists at all. It is probably less than 100-200 gammas. (A gamma is 10^{-5} gauss, and the earth's field is of the order of half a gauss.)

The topography and microstructure of the lunar terrain could be discussed at length; they undoubtedly influence propulsion systems operating on the moon but their influence is indirect. The same is true of many other environmental features, and the present report must be restricted to the most relevant factors. Among these, the vacuum, radiation, and thermal environments appear to be the most important for propulsion systems; they have been described, at least briefly, in the foregoing discussion.

D. MARS

Mars may be the only planet, other than the earth, on which instrument packages and scientific exploration teams can be based to study the solar system in more detail. Venus has a surface temperature too high to make landing feasible (700°K) and further, since it has a thick cloud layer, is less suitable as an observation platform. The atmosphere of Mars is highly transparent in most optical frequencies, making it a good choice for an astronomical base. A summary of the Martian physical environment is presented below. Other descriptive information is presented in the annotated bibliography, Ref. 120 to 167.

1. Physical Properties

The diameter of Mars is about 6626 km, making this planet about one-half as large as the earth, while its mass is only 10.8% of that of the

II Planets and Their Satellites, D (cont.)

earth. As a result, the mean gravitational acceleration on the surface of Mars is only about $1/3$ that of the earth.

More precisely, the limiting values of the mass and radius (earth units) range from 0.1069 to 0.1080 and 0.521 to 0.539. Using these values, the calculation of surface gravity yields 0.368 to 0.398 of that of the earth (Ref. 140).

The only serious uncertainty concerns the ellipticity of the lobe. This has been measured in two ways which give different results: observations of the Martian satellite orbits give the dynamic ellipticity usually quoted of 0.00522, while the optical measurements (determined by measuring the flattening of the disk with a micrometer) give a value two or three times larger, or about 0.013. The reason for this discrepancy has not yet been found.

The two satellites observed in the ellipticity measurement are located at distances of 9000 and 23,000 km from the Mars center, respectively. The inner satellite, Phobos, has approximately twice the diameter of the outer satellite, Deimos. Both are probably less than 10 miles across. Little information is available concerning their natural environment. Shaw (1961, Ref. 127) reports that "it is inferred they will have no atmosphere, a mean temperature similar to Mars but of greater extremes and a rough irregular surface covered with dust."

2. Clouds and Haze

Observers have identified three general categories which have different colors and somewhat different properties: yellow clouds, presumably dust, which form in limited areas and move with the wind; white clouds, probably composed of ice crystals or possible CO_2 crystals; and blue haze, which covers extensive areas and is the subject of considerable speculation. Possible explanations of the haze include: a gravitational settling of suspended particles, a phase change of a condensable or sublimable substance, ice-crystal layer of a particular diameter with special back scattering properties, trapped solar protons, and others. The blue haze (probably red to the

II Planets and Their Satellites, D (cont.)

eye since it extinguishes blue light) remains one of the Martian enigmas. The question of the blue haze is not wholly academic, since the albedo is strongly influenced in this short-wave region, making accurate heat balance of space vehicles difficult.

3. Surface Characteristics

The distinguishing surface features are: dark areas, predominantly neutral-grey in color, localized near the equatorial regions; bright areas, of orange ochre, covering most of the remainder of the planet; and a white polar cap. Mars usually has a polar cap at all times in one hemisphere or the other. The polar caps are time-variable; they diminish in area as local summer approaches and one or the other sequentially disappears entirely before reforming the following winter. It is now well established that the polar caps are not frozen CO_2 but are probably ice.

In attempting to predict meteorological phenomena, Shilling (Ref. 128) has suggested that a study of the Chang Tan desert in Tibet may offer some clues about the nature of the Martian surface. The peculiarities of climate and flora of this wide plateau, 17,000 feet high, make this desert markedly different from other high-desert areas on earth. Others attempting to match the polarization curve with terrestrial samples of various surface materials have concluded that the surface is largely covered with opaque granules. No volcanic activity has been observed.

4. Atmosphere

The only molecule which has been identified unambiguously by spectroscopic means is CO_2 , constituting about 2.2% of the atmosphere. This is about 14 times more CO_2 than exists on the earth. The composition of the remaining 97.8% of the gas is inferred to be molecular nitrogen, with a possible admixture of inert gases. Water vapor is believed to be an order of magnitude less than found on the earth (Ref. 127).

The vertical structure of the Martian atmosphere has been calculated based on a number of different atmospheric models. Shilling (Refs.

II Planets and Their Satellites, D (cont.)

120 and 131), for example, constructs three model atmospheres believed to encompass the possible extremes:

<u>Model No.</u>	
I	Convective equilibrium throughout (a purely theoretical construct not believed to represent the likely conditions on Mars)
II	Convective equilibrium to an assumed tropopause level and conductive equilibrium above (most likely or best atmosphere)
III	Conjectural model, based on the assumption that an appreciable amount of ozone exists in the upper atmosphere, as argued by Shilling.

The mean values of atmospheric parameters near the surface on which Shilling based his calculations are given in Table 9. The vertical variations of temperature, pressure, and density as predicted by the three models are given in Tables 10, 11, and 12. Graphical representations of these atmospheres compared with the earth ARDC 1959 model atmosphere are presented in Figures 16, 17, and 18. A comparison of the extreme ranges of pressure with the earth's atmosphere is shown in Figure 19.

These values have been presented in some detail since the minimum values of Model II and the maximum values of Model III are believed to represent, with considerable confidence, the possible limiting values. Other extreme models (Ref. 121) have been proposed which also yield high-, low-, and medium-temperature classes. Since these (Ref. 121) exponential atmospheres are generally held in less favor by astronomers (Ref. 131), discussion is limited here to the more widely accepted calculation of Shilling.

5. Albedo

The albedo of Mars is a strong function of wavelength at 7000A; the albedo is about 0.3 declining rapidly to about 0.04 below 4500A; the region of the blue haze (Ref. 123). The reflectivity at any given

II Planets and Their Satellites, D (cont.)

wavelength varies with position on the surface; representative albedos of the bright and dark areas are 0.15 and 0.05.

An average albedo of 0.15 is generally accepted (Ref. 142); variations of this mean from 0.148 to 0.154 are given by Kirby (Ref. 140).

6. Absence of Magnetic Fields and Radiation Belts

No indication of a Van Allen belt of any significant intensity has been observed on Mars. If a magnetic field exists, it is probably substantially weaker than that of the earth (Ref. 146). Kopal originally felt that the magnetic field was negligible (Ref. 141) but has recently conjectured higher intensity fields (work to be published).

E. JUPITER

Although no flights to Jupiter are planned for the immediate future, such explorations will eventually be made. It is therefore appropriate to consider briefly some of the characteristics of Jupiter in order to ascertain, in at least a preliminary way, what some of the propulsion problems might be.

1. Physical Properties

Jupiter is the largest planet in the solar system, larger in fact, than all the other planets put together. Because of its great size, Jupiter causes serious perturbations in the orbits of other planets and planetoids. Its influence on the motion of other bodies makes the study of Jupiter extremely important in celestial mechanics.

Jupiter has 12 known satellites. It has been suggested that one of the larger satellites might be used as an observation base. Of these, the four largest, called the Galilean satellites, have been studied in some detail because of their densities; the first two are believed to be of rock, while the third and fourth may be solid carbon dioxide or ice. Characteristics of the satellites are given in Table 4.

II Planets and Their Satellites, E (cont.)

2. Clouds

Jupiter is covered with brilliantly colored clouds, ranging from red and brown to bluish white. Different cloud altitudes are observed to have different rotation periods. The violent cloud motions and high-level turbulence observed in the atmosphere are believed associated with the high speed of rotation of the planet coupled with a very thick atmosphere.

These clouds have been the subject of much speculation; considerable factual information concerning their development, motion, relative velocity, and color has been gathered. It has been proposed that the colors may be due to various solutions of metallic sodium in liquid or solid ammonia. Recently Spinrad (1962, Ref. 101) found that the Jovian ammonia rotates at a much slower speed than the cloud layer, slower by 6 km/sec. Depending on the extent of the vertical distance out from the planet covered by this motion, a jet stream of sizable proportions could exist.

3. Surface Characteristics

It is inferred that beneath the turbulent atmosphere a solid surface exists. Although no surface features are visible, certain semi-permanent markings have been observed. The Great Red Spot is the most prominent. This large area, about 30,000 miles long and 7,000 miles wide, has gradually faded away, losing its red color and becoming rounder in form. Observation has indicated however, that the Great Red Spot, as well as other semi-permanent markings, are not permanently attached to a solid surface but behave more as a solid floating in a liquid medium.

4. Atmosphere

Methane, ammonia, and hydrogen have been identified spectroscopically in the Jovian atmosphere. Helium has not yet been detected although its presence is inferred from studies of Uranus and Neptune. Nitrogen is not believed to be present because of inconsistencies with molecular weight calculations. The abundance of these constituents is not known. It is thought that approximately three times as much helium as hydrogen is present (Ref. 101) but

II Planets and Their Satellites, E (cont.)

Zabriskie warns (Ref. 103) that this concept of Jovian atmosphere may require substantial revision. Based on reference data of Uranus and Neptune, the following composition is computed by Trafton (1962, Ref. 102) using a method suggested by Kuiper (see Ref. 102 sub-listing):

135 km-atm of hydrogen

373 km-atm of helium

3 km-atm of ammonia.

The abundance of these element, except helium, has been measured above the cloud layer. Based on these measurements (and estimating the helium concentration), the total pressure above the clouds was computed by Trafton (1962) to be:

	<u>NPT Density</u> <u>g/cm³</u>	<u>Jovian Abundance</u> <u>km-atm</u>	<u>Partial Pressure</u> <u>Atmospheres</u>
H ₂	8.9 x 10 ⁻⁵	5.5	0.048
He	17.8 x 10 ⁻⁵	16.5	0.285
CH ₄	71.4 x 10 ⁻⁵	0.15	0.010
NH ₃	75.9 x 10 ⁻⁵	0.007	<u>0.001</u>
		Total	0.36 atm

5. Temperature and Thermal Structure

Little is known concerning the temperature distribution in the atmosphere or the energy balance of Jupiter. The maximum radiation temperature is 120°K. Temperatures above the cloud layer have been determined as 170-200°K (Zabriskie, 1960) and 165-168°K (Kuiper, 1949). Microwave radiation yields various temperatures depending on the wavelength:

<u>Wavelength</u>	<u>Disk Temperature</u>	<u>Source</u>
10 μ	140 ± 10	
3.03 cm	171 ± 20	
3.15	145 ± 18	Mayer (0.959)
3.17	173 ± 20	Giordmaine, et al. (1959)

II Planets and Their Satellites, E (cont.)

<u>Wavelength</u>	<u>Disk Temperature</u>	<u>Source</u>
3.36	189 $\pm$ 20	Giordmaine, et al. (1959)
3.75	200 $\pm$ 200	Drake and Ewen (1958)
10.2	640 85	Sloanaker (1959)
21	2500 450	McClain (1959)
22	3000 1700	Drake and Hvatum (1959)
31	5500 1500	Roberts and Stanley (1959)
32	7500 2500	McClain (1959)
68	70,000 30,000	Drake and Hvatum (1959)

Various theories have been proposed to account for these high temperatures; cyclotron and synchrotron theories account for both the radiation intensity and for the strong polarization (Ref. 105). Another theoretical model proposes that Jupiter produces heat internally by gravitational contraction. Much additional information is needed before the problem is resolved.

6. Albedo

The albedo of Jupiter is believed to have a value of not less than 0.64 nor more than 0.82. The most recently calculated value (Traften 1962) is 0.73. The older values of 0.51 (Kuiper and Harris, 1949) and 0.44 (Schonberg, 1921) are considered too low. The reflectivity was recently measured by an Aerobee rocket experiment to be 0.26 ± 0.04 at 2700°A .

7. Magnetic Fields and Radiation

It has been reasonably well established that Jupiter has a Van Allen radiation belt many orders of magnitude greater than that of the earth. This is verified by the extremely high intensity radiation measured from radio waves (Ref. 108) and as in agreement with cyclotron theory predictions. While agreement has not yet been reached as to the value of magnetic field (maximum value may be as high as 10,000 gauss, with radiation intensity a trillion times that of the earth), there appears to be little doubt that the fields are very large, posing serious problems.

II Planets and Their Satellites (cont.)

F. SATURN

Saturn's size is deceptive, for although its diameter is almost equal to that of Jupiter, it is not even a third as massive. Its density is extremely low (0.71); it is the only planet that would float if it were placed in a big enough ocean. Like Jupiter, this suggests a much smaller solid core than its visual disk indicates, surrounded by large quantities of lighter material such as ice and frozen ammonia.

1. Atmosphere

Absorption bands of great intensity indicate large quantities of ammonia and methane. The former is not nearly so abundant as on Jupiter, since the cooler temperatures of the ringed planet cause more of the ammonia to freeze out. This results in a greater penetration of sunlight into the methane of the atmosphere (Ref. 168). More regular than those of Jupiter but less distinct, the bands of Saturn range in color from the broad yellowish band around the equator to the greenish caps of the poles. The atmosphere is fairly deep, but its precise depth thickness is not yet known.

In 1962, Guido Munch, of the Mt. Wilson and Palomar observatories, and Hyron Spinrad, of the Jet Propulsion Laboratory, discovered molecular hydrogen in the atmosphere of Saturn. This evidence supports the widely held opinion that the atmosphere of Saturn is largely hydrogen and helium, similar to the primordial sun. They also detected evidence of very high winds causing the gases to be swept into the three observable bands.

2. Temperature

Infrared radiometric observations yield a surface temperature of 123°K . This is in close agreement with the recent blackbody disk temperature of $106 \pm 21^{\circ}\text{K}$ obtained from radio emissions at 3.4 cm by the University of Michigan. The temperatures which a vehicle will encounter in space at Saturn's orbit will make it unnecessary to shield or rotate it to prevent heat deformation by the sun.

II Planets and Their Satellites, F (cont.)

3. Rings

The reflection spectrum of the rings appears to be very similar to that of the Martian polar cap. This leads Kuiper to conclude that the particles are either covered by frost or made entirely of ice (Ref. 33). They, along with the inner satellites, are considered to be atmospheric condensations, the rings not having formed a satellite because they are within the Roche limit of Saturn.

Because of uncertainty regarding the depth of the atmosphere and the existence of a solid surface coupled with the high escape velocity of the planet, exploration will be limited to observation of the ringed planet from one of its nine satellites for some time to come.

4. Satellites

The physical data of Saturn's satellites is presented in the general tables on the solar system. Of the nine satellites, the first five are grouped close to the planet. Minias, Enceladus, and Tethys are probably made up largely of snow, since they are less dense than water (Ref. 33). Their surfaces, therefore, may not be very firm. Yet Minias would provide a good observation base for observing Saturn at close quarters, as it makes a complete circuit of the planet in less than a day.

Dione, Rhea, and Hyperion probably have a rock core surrounded by ice, snow, or even solid ammonia. Traces of methane gas probably make up tenuous atmospheres on these small globes (Ref. 169).

Although Minias has the advantage of being close to Saturn for observational purposes, it has the disadvantage of Saturn's static and electromagnetic field effects on earthbound radio signals. Titan, Saturn's largest satellite, is far enough from its primary to alleviate this and is in view of the earth for as long as a week at a time. It could provide a stable platform, as it is comparable in size to the planet Mercury. Its methane atmosphere makes it unique and provides a definite source of fuel for rockets in the area. It might be profitable to establish a permanent refueling

II Planets and Their Satellites, F (cont.)

base on this satellite in the distant future to service vehicles exploring the outer reaches of the solar system. Such a refueling capability would enable the use of shorter hyperbolic trajectories in preference to the slow minimum-energy orbits. Titan's planetary-sized atmosphere would help in its own exploration since it could support aircraft. Estimates of Titan's diameter vary from the standard 4200 km, to 5050 km, measured by Carmichael (Ref. 32).

Beyond Titan, two more satellites, Japetus and Phoebe, complete Saturn's known satellite system. Japetus is of interest because one side shines five times brighter than the other, indicating that an anomaly exists in its surface structure. Phoebe, on the other hand, is distinguished by its retrograde motion about Saturn.

Since all of the above nine satellites are larger than Jupiter's smallest six, it seems likely that a few small satellites have yet to be detected.

G. URANUS AND NEPTUNE

Uranus and Neptune are very similar in all observable characteristics. Both appear as green disks in the telescope because of the many intense absorption bands in the red region of the spectrum. They are typical of Jovian planets having low densities and large diameters. Neptune, though slightly smaller, has a density of 2.47, compared to a density of 1.56 for Uranus. Bi-durnal variations in the brightness of Neptune suggest two more or less antipodally situated regions of high albedo, a condition which could be due to an anomaly in Neptune's structure (Ref. 33).

1. Atmosphere

The spectra of the two planets reveal large quantities of methane, with little or no ammonia. Kuiper, however, holds that the methane of Uranus is not methane at all, but something resembling formaldehyde (Ref. 33). Because it is too cold for ammonia to remain in the gaseous state, our telescopes can penetrate farther into these atmospheres than those of Jupiter and Saturn. While it had been assumed that all of the giant planets contain

II Planets and Their Satellites, G (cont.)

large quantities of hydrogen and helium (because of their low density), none had been observed. Studies of Neptune, and more recently of Saturn, however, have spectroscopically detected hydrogen, giving support to the above assumption (Ref. 168).

2. Temperature

Because of their great distance from the sun, Uranus and Neptune have average temperatures of 49°K and 40°K , respectively. As in the case of the other giants, their surfaces are not visible and it is unlikely that vehicles will be landing on these two planets for some time to come, if ever. A final determination will have to await further information on the type of observation.

3. Satellites

The small size and great distance of these satellites makes possible only a scant knowledge of them. Uranus has five about the size of Saturn's inner group. They technically revolve in a retrograde direction, since the equator of Uranus is inclined 98° to its orbital plane. As a result of this unusual configuration, direct line-of-sight radio communication will be possible with the earth most of the time. Radio travel time, however, will be extended because of the great distance.

Of Neptune's two satellites, Triton and Nereid, the former is more interesting, as it is closer to its primary and as big as Titan. No atmosphere has been detected; its physical dimensions are not certain, but its surface is considered to be similar to that of Pluto.

H. PLUTO

The discovery of Pluto in 1930 was the result of a careful search brought on by a mathematical prediction of its existence. Little is known about this remote world other than its orbital elements. Its highly eccentric orbit carries it closer to the sun than Neptune at perihelion and more than 40 A.U. distant at aphelion, in a plane making an angle of 17° with the ecliptic.

II Planets and Their Satellites, H (cont.)

The planet's magnitude, according to available measurements, shows a periodic variation of 0.11 mag every 6.390 ± 0.003 days and is believed to indicate the duration of Pluto's day (Ref. 168). The 0.16 albedo is probably due completely to surface reflection, as all atmospheric components but hydrogen would freeze out and cover the surface in its 45°K temperature (Ref. 169). Its surface is believed to be fairly rough because of collisions with meteors, comets, and the effects of its cold environment.

Such basic quantities as the mass, diameter, and density, however, are more difficult to determine in the case of Pluto. Because it has no satellites, its mass must be determined by its perturbations on Uranus and, especially, on Neptune. All such determinations depend on doubtless inaccurate observations of Neptune made by Lalande in 1795 (Ref. 168). As a result no reliable, gravitationally determined estimate of the mass of Pluto is now available. The mass estimate generally favored puts it between the values of the earth and Venus.

Kuiper has measured its diameter at 3600 ± 200 miles in the 200-inch telescope. This value, coupled with a high mass value, could mean that Pluto is the densest planet in the solar system (Ref. 33). Surely it is terrestrial in type and bears no relation to its Jovian companions.

As in the case of Uranus and Neptune, the most severe requirements placed on the vehicle will be the long transit times and the intense cold. Pluto's high inclination to the ecliptic will necessitate the use of extra energy during transfer, even though it will be about as close as Neptune for the rest of the twentieth century (Figure 2). Specific vehicle requirements for landing on Pluto will remain unknown until the planet can be observed from closer range, possibly from a probe traveling as far as the orbit of Uranus.

III. RADIATION AND SPACE DEBRIS HAZARDS*

The two major hazards of the interplanetary environment, aside from the vacuum difficulties, are (a) damages due to the interception of various types of radiation, and (b) collisions with space debris. Although initial predictions of the severity of the radiation and collision hazards indicated that both effects were overestimated, newer data show the problems to be formidable.

The principal types of radiation to be encountered consist of the continuous electromagnetic radiation from the sun and various types of particle radiation, including galactic cosmic rays, solar flares, and trapped radiation such as that found in the Van Allen belts. The principal space debris hazard lies in the abundance of hypervelocity micrometeoroids.

Our present knowledge of the interplanetary environment is so quantitatively incomplete - and concepts and ideas develop or change so rapidly - that a description of this environment, as now understood, cannot be presented simply as a collection of formulas, tables, and graphs. Therefore, the description of the space environment is given in the form of a concise discussion combined with tables and graphs showing the best, or otherwise typical, quantitative information. In this way, the most intelligent use of existing data can be made. Before use is made of any particular figure or table, it is recommended that the relevant discussion be read.

A. INTRODUCTORY COMMENTS

The task of putting together all the data acquired from space probes, satellites and earth based observatories has been likened to a cosmic jigsaw puzzle (Reference 170). Bits and pieces of data are assembled, as they are obtained, by many people throughout the scientific community; this jigsaw puzzle goes together so gradually from so many different viewpoints that frequently the design engineer finds himself both overwhelmed with descriptive literature and bewildered by conflicting interpretations.

* Portions of this section have been adapted from material originally prepared for Contract AF 04(611)-7441, "Rockets In Space Environment."

III Radiation and Space Debris Hazards, A (cont.)

Within the past year, with the acquisition of newer data and a more detailed study of older work, many of the apparent conflicts have been resolved and a greater confidence developed in our understanding of the space environment. For example, M. Neugebauer and C. Snyder (Reference 171) show that the Mariner II data on the plasma flux is in good agreement with the earlier Explorer X and Luniks results, with the Mariner giving a much superior "average" value owing to the extremely long sampling time. Furthermore, Johnson (Reference 172) reports that the Explorer XII resolved the problem which existed regarding the magnitude of the Van Allen belt electron flux in favor of the lower value of $10^8/\text{cm}^2\text{-sec}$. With regard to micrometeoroid flux, Whipple (Reference 173) in summarizing flux and penetration problems points out the improvements now possible due to better measuring techniques and more abundant data.

Further study research can usually be expected to uncover a number of new problems, some of which may prove more complex than those solved. In general, though, the process of acquiring and evaluating new data and comparing it with previously determined results concepts soon establishes meaningful physical models on which realistic design criteria can be established. In some cases this may be within a year or so. M. Malitson (Reference 174) has pointed out that major solar flare events were discovered only in 1946, and that solar cosmic radiation has been investigated in detail only since 1956. Although it is true that improvements are needed in our understanding of the basic physics of the sun before the problem can be resolved completely, it is also apparent that the statistical studies of measurements obtained since 1956 have greatly increased our confidence in predicting major solar flare events. Conversely, the systematic collection of solar flare data did not lead at once to any unified agreement on the structure of the interplanetary magnetic fields, since as C. Warwick (Reference 175) points out, the magnetic models derived by various research workers depended in many cases on which of the relations the authors chose to summarize. It might be pointed out that the Mariner II data has done much to resolve this controversy (Reference 171).

III Radiation and Space Debris Hazards, A (cont.)

Therefore, even though much essential data is not yet available and our understanding of many important processes is grossly inadequate, it must be admitted that the amount of meaningful information available for evaluating practical design problems is quite substantial. In most cases it is not possible to present this work in compact form, since the necessary "similarity" relations are not yet known. Many charts and tabulations must therefore be included.

B. ELECTROMAGNETIC RADIATION

The total flux of electromagnetic radiation from the sun is surprisingly constant over a year's time, even during violent disturbances observed on the sun's surface. The energy output of the solar surface into space is about 44 megawatt/m². At the earth's distance the value is about 1.36 kw/m². The solar radiation energy varies inversely with the square of the distance from the sun and can be computed from

$$S = \frac{9.05 \times 10^{25}}{4\pi R^2}$$

where 9.05×10^{25} cal/sec is the bolometric luminosity of the sun and R the solar distance. Values for this radiation as a function of distance from the sun are shown in Figure 20. The radiation equilibrium temperature of a blackbody depends only on the solar radiation intensity (distance from the sun) and on the body shape, assuming that no other heat sources are present. Typical radiation equilibrium temperatures for a spherical blackbody are shown as a function of distance from the sun in Figure 21. The extremely limited temperature range tolerable by humans is noted; propulsion system components, of course, can withstand a much wider temperature range.

The bulk of the energy in the solar spectrum lies between 0.3 and 4.0μ with approximately 1% of the energy lying beyond each of these limits.

The electromagnetic radiation of the sun as seen at the earth outside the atmosphere consists of a (1) continuous spectrum in the near-ultraviolet, visible, and infrared regions containing many absorption lines

III Radiation and Space Debris Hazards, B (cont.)

(Fraunhofer lines), and (2) a number of emission lines at shorter wavelengths which contribute only a small amount of energy, compared with the continuum. Rocket observations have shown that the continuous spectrum diminishes very rapidly in intensity with decreasing ultraviolet wavelength and that, below 1400 Å, the sun radiates a continuous spectrum with emission lines superimposed upon it. This is unlike the visible and near-ultraviolet where the continuum is crowded with intense absorption lines and there are no emission lines.

The continuous spectrum can be well approximated in various wavelength intervals by blackbody radiation of a specified temperature. For example, the visible and infrared regions show a spectral irradiance corresponding rather closely to that of a 6000°K blackbody source. The temperature of a blackbody that most nearly matches the continuous spectrum of sunlight in total energy output is about 5750°K. The distribution of energy in sunlight outside the earth's atmosphere is shown in Figure 22 (Johnson, 1961, Reference 176). The ultraviolet region where emission lines become prominent is shown in more detail in Figure 23 and is taken from the work of Detwiler, Purcell, and Tousey of N.R.L. (Tousey, 1961, Reference 177). From 1040 to 912 Å, the spectrum consists mostly of emission lines which are not resolved in the 10 Å-interval plot. The extreme ultraviolet shown in Figure 23 originates from higher levels in the sun's atmosphere than does the near-ultraviolet and the visible. The continuum in the ultraviolet region of Figure 23 probably comes mainly from the low chromosphere, where the temperature is of the order of 4000 to 5000°K. The emission lines at short wavelengths originate in still higher regions of the solar atmosphere, where the temperature ranges from 5000°K in the chromosphere to millions of degrees K in the corona. The exact region of emission depends on the particular line.

An important series of emission lines is the Lyman series in the hydrogen spectrum, with the first line, Lyman alpha, at 1216 Å. The Lyman-alpha line carries about 6 erg/cm²-sec near solar maximum and delivers more energy than the entire solar spectrum from wavelengths shorter than itself. The intensity is probably less at sunspot minimum. The higher members of the

III Radiation and Space Debris Hazards, B (cont.)

series are followed by the Lyman continuum, which is the most important emission below 912 Å. It follows a 6700°K blackbody curve. At 584 and 304 Å there are intense emissions by neutral and ionized helium, respectively. The two lines produce on the order of 0.5 erg/cm²-sec at the earth (Hinteregger, 1960, Reference 178).

The solar constant, the total solar irradiance at the earth's mean distance from the sun, as given by Johnson (1954, Reference 180), is 2.00 ±0.04 cal/cm²-min, (1.39 x 10⁶ erg/cm²-sec = 443 Btu/ft²-hour) and does not vary significantly with the solar cycle. The solar spectrum in 50 Å-steps from 0.22 to 7 microns (1 micron = 10⁴ Å = 10⁻⁴ cm) is given in Table 13 where H_λ is spectral irradiance and P_λ is the percentage of the solar constant associated with wavelengths shorter than λ (Johnson, 1954, Reference 180).

The region below 3000 Å is shown in great detail in Tables 14 and 15, which are taken from Hinteregger (1961, Reference 179), who has evaluated recent measurements. Table 14 shows rounded-off values taken or averaged from work published through 1960. In the region where the table of Johnson and that of Hinteregger overlap, Johnson's values are lower by as much as 40%. Johnson's values are based on early N.R.L. rocket data and are considered by Tousey (1961, Reference 177) to be too low at lower wavelengths. Hinteregger's data should be considered the more accurate of the two.

The comments below apply to Tables 14 and 15 and give definitions and explanations of the notation used.

The radiation spectrum is described both in terms of photon-flux density, Φ , and in terms of energy-flux density, I . The dimensions of Φ and I are given in the column headings. $\Phi(\lambda)$ and $\Phi(\lambda_1/\lambda_2)$ are integral fluxes of photons defined as

$$\Phi(\lambda) = \int \Phi_\lambda d\lambda$$

(integral over the specific line around λ)

III Radiation and Space Debris Hazards, B (cont.)

$\Phi(\lambda)$ has dimensions of photons/cm²-sec and

$$\Phi(\lambda_1/\lambda_2) = \int_{\lambda_1}^{\lambda_2} \Phi_{\lambda} d\lambda$$

(integral over all lines and/or continua)

$\Phi(\lambda_1/\lambda_2)$ has dimensions of photons/cm²-sec, where Φ_{λ} designates the differential spectral photon-flux density. For example, from Table 14, the flux of photons in the interval 2800 to 3000 Å is 1.5×10^{15} photons/cm²-sec and from Table 15 the photon flux for the Si-III line is 4×10^9 photons/cm²-sec. These are values estimated for the top of the atmosphere. It should be noted that the convention that $a \times 10^b = a^b$ is followed in both Tables 14 and 15. Similarly, the intensities are also defined as integral fluxes

$$I(\lambda) = h\nu \cdot \Phi(\lambda),$$

where h is Planck's constant and ν is the frequency corresponding to the wavelength λ . The dimensions of $I(\lambda)$ are erg/cm²-sec. In an analogous way:

$$I(\lambda_1/\lambda_2) = \int_{\lambda_1}^{\lambda_2} h\nu \cdot \Phi_{\lambda} d\lambda$$

In using the tables it is important to notice that photon flux Φ or intensity given for a particular wavelength interval includes certain lines indicated, only the continuum, or both lines and continuum in the interval. For example, the intensity in the interval 1200-1300 Å including only the continuum is 0.08 erg/cm²-sec. The total intensity including lines and continuum is 3.5 erg/cm²-sec.

Both tables list more-or-less empirical values of a certain altitude h^* in the earth's atmosphere, defined as the level at which the specified

III Radiation and Space Debris Hazards, B (cont.)

solar photon-flux is reduced to the fraction $1/e$ of the corresponding flux on top of the atmosphere for an overhead sun. Both of Hinteregger's tables are reproduced intact, and they contain much information beyond simply specifying what is known about the solar spectral intensities.

The basic measurements for Tables 14 and 15 come from rocket-borne experiments at various altitudes high in the atmosphere, and the estimates given for the top of the atmosphere are based primarily on simple extrapolations of the observed vertical-attenuation profiles rather than on any assumed "atmospheric models." When satellite solar-spectral observations are made, this uncertainty will be removed and in addition much information about the atmosphere can then be inferred.

The average incident fluxes of solar photons from the visible to the nearer-ultraviolet region are known to be more or less constant throughout a full solar cycle. This includes the data of Table 14. The extreme ultraviolet region ($\lambda \lesssim 1300$ A, Table 15) shows both long-term variations over a solar cycle and short-term variations during solar flares. Empirical data on these variations is extremely meager. Transient variations produced by flares are probably much more pronounced in the X-ray region than for longer wavelengths of approximately 100 A. This distinction has been experimentally established for the Lyman-alpha line by Friedman, who has shown that the total solar Lyman-alpha flux remains more or less constant even during major solar flares (Friedman, 1961, Reference 181). The long-term variation of the Lyman-alpha line over a solar cycle is, however, not well-known. The situation is even less satisfactory for the other emission lines, and no reliable picture of systematic variations of Φ (100/1300 A), i.e., the integrated photon-flux from 100 to 1300 A, can be given as yet.

Upper limits for the intensities of solar-flare X-rays are given in Table 15. Also to be mentioned when considering the time variation of the solar spectrum are the radio-noise bursts which occur around several hundred megacycles. These have been classified as Types I through IV and are of great complexity.

III Radiation and Space Debris Hazards, B (cont.)

As emphasized above, these variations have no significant effect on the solar constant. References mentioned in Tables 14 and 15 are listed separately in the bibliography.

C. SOLAR FLARES

Solar flares are explosive outbursts of electromagnetic radiation (including radio, ultraviolet, and X-ray wavelengths) and ionized matter (primarily protons and electrons) from the vicinity of sunspot groups. They are catastrophic disturbances having a sudden onset and a gradual decay, usually taking less than an hour. On reaching the earth in approximately 8 min, the ultraviolet- and X-radiation greatly increase the ionization in the D-layer of the ionosphere (50 to 100 km above the earth).

1. Observation of Flares

To investigate such abnormal ionization, data on $W_{\min}$ in ionograms are useful. $W_{\min}$ is defined as the minimum frequency of radio waves at which ionospheric echoes are observable; its time variation depends on the electronic density in the lower ionosphere. The value of $W_{\min}$ increases when the excess X-radiation reaches the earth (S.I.D. or Sudden Ionospheric Disturbance effect). Solar-flare particles frequently follow the enhanced X-radiation, reaching the earth some time after the visible flare and producing increased ionization over the polar-cap regions. As a result, all ionospheric echoes may be completely masked, causing "polar blackouts." Unlike ordinary auroral-zone ionizations, these abnormal ionizations indicate the precipitation of particles over the whole polar cap, which suggests an isotropy of incoming particles.

Another technique for observing the ionospheric effects due to ionization by solar-flare energetic charged particles has been developed primarily by Little, Leinbach, and Reid (1958, 1959, References 182, 183 and 184). The absorption of incoming cosmic radio noise at 27.6 mc is observed after passing through the ionosphere, and the changes in the absorption due to increases in ionization of the 50-to-100-km level are recorded and interpreted

III Radiation and Space Debris Hazards, C (cont.)

as the arrival of protons in the energy range of 10 Mev and higher. This is called Type III absorption or "polar-cap absorption" and has been observed over a wide range of longitudes in the polar regions. Within the last two years solar flare particles have also been observed directly by means of high-altitude balloons, rockets, and satellites.

2. Energy Levels

The great majority of solar flares which produce bursts of particles reaching the earth do not produce particles attaining relativistic energies. Comparatively rare, large-scale events do, however, produce a spectrum of particles reaching cosmic-ray energies of 40 Bev. Protons of energy greater than about 2 Bev produce secondary nucleonic components observable at ground level, and relativistic solar flare events are now immediately detected by many neutron-monitor stations and meson detectors throughout the world. There seems to be a gradual transition between the relativistic and the non-relativistic solar-flare events, with the latter much more frequent.

3. Sequence of Events

The sequence of events following a major relativistic solar flare (23 February 1956) is described by J. A. Simpson (1961, Reference 185) as follows: "The first arriving particles come to the earth from a limited-source direction in the sky.* The apparent source is a relatively large area which includes the sun. Initially the particles are of the highest energies in the flare spectrum; subsequently the whole sky becomes 'illuminated' with particles extending to lower energies; for these low-energy particles, and late-arriving high-energy particles, there appears to be remarkable isotropy. Following the onset of isotropy, the particle intensity gradually diminishes with the flare spectrum essentially unchanged . . . The intensity at the earth is observed to diminish to its preflare level within a period of 15-20 hr."

Simpson also describes the sequence of events for a non-relativistic flare: "The first high-energy particles (on the order of 10^2 Mev)

* The first particles arrived about ten minutes following the onset of the flare.

III Radiation and Space Debris Hazards, C (cont.)

arrive within 1-5 hr following the solar flare. On only a few occasions has the first arrival of high-energy radiation been delayed more than 4 or 5 hr. . . The particles are observed to arrive over the entire polar cap and down to latitudes limited only by the prevailing geomagnetic cutoff. Particles continue to arrive for a period of many hours to several days following a solar flare. In a manner typical of large solar flares, a low-energy beam or plasma region independently reaches the earth within about a day following the flare to produce a geomagnetic storm. The low-energy particles continue to arrive throughout the geomagnetic storm effect and, in addition, are observed at geomagnetic latitudes which normally forbid their arrival. . . An outstanding feature of these low-energy bursts is the very high flare-values attained on some occasions."

4. Frequency of Flares

The annual frequency of the nonrelativistic solar-flare events is indicated in Figure 24, which covers an 11-year period (Geodeke, 1961, Reference 186). The frequency of occurrence is in phase with the solar cycle and shows maxima near the equinoxes (22 March and 22 September) and minima in June and December in the northern hemisphere.

There have been ten relativistic events observed since the first one was detected on 28 February 1942. Figure 25 gives the frequency of both relativistic and nonrelativistic events over a solar cycle (Dessler, 1961, Reference 187). The frequency of the nonrelativistic events in Figure 25 was inferred from polar-cap absorption studies.

5. Flux and Spectrum

It has been mentioned in the preceding paragraphs that the sun emits various kinds of particles, primarily protons and electrons, ranging from thermal to relativistic energies. The knowledge of the energy spectrum of particles ejected from the sun is still incomplete. Of special importance is the uncertainty in the maximum particle-flux one can expect from a solar flare. Obayashi and Hakuha (1960, Reference 188) have combined the observations

III Radiation and Space Debris Hazards, C (cont.)

of many investigators and their resultant integral energy-spectrum of solar particles is presented in Figure 26. The positions of flares on the solar disk and the magnetic type of their associated sunspots have an important bearing on the magnitude of the particle flux reaching the earth, as does the state of the magnetic field between the earth and the sun. A certain range in observational results is therefore expected and is indicated in Figure 26 by the shaded area. Associated with general solar activity and included in the figure are spectra for interplanetary thermal particles near the earth of temperature 2×10^5 °K, according to Chapman (1957, Reference 189). The fluxes are computed using this temperature and densities of about 600 particles/cm³, from observations of zodiacal light (Siedentopf, et al. 1953, Reference 190). Also included are proton spectra of solar plasma clouds and the solar wind which are labeled solar corpuscles in the figure. A plasma cloud of this energy (about 1000 km/sec) emitted by a solar flare penetrates into the geomagnetic field until the particle energy density approximately equals the energy density of the magnetic field. This theoretically occurs around ten earth radii. Plasma particles then appear to contribute to the development of a diamagnetic-ring current at about five earth radii. This current causes the main phase of geomagnetic storms. However, these particles do not directly form a part of the space environment within at least five earth radii.

The following comments apply to Figure 26. The information about solar particles of the highest energy is derived from the cosmic-ray intensity increases associated with the great solar flare of 23 February 1956, which yields the spectrum of relativistic protons (Meyer, et al., 1957, Reference 191). This is indicated by the curve labeled (1) in the figure and, for comparison, the energy spectrum of normal cosmic rays is also shown (J. A. Van Allen and A. F. Singer, 1950, Reference 192). The late effect of the flare gives information about the spectrum for nonrelativistic particles. Abnormal ionization of the polar ionosphere began gradually and reached a maximum a few hours after the flare. D. K. Bailey (1959, Reference 193) showed that protons of

III Radiation and Space Debris Hazards, C (cont.)

10 ~ 1000 Mev are responsible for this and, on the basis of balloon observations of the spectrum at about the 1-Bev range (Van Allen and Winkler, 1957, Reference 194), he constructed the curve labeled (2) in Figure 26. Thus, curve (1) gives the flux first reaching the earth from the relativistic flare of 23 February 1956 and curve (2) gives the flux 18 hours later for this same flare. The spectrum in the energy range 1~100 Mev is obtained from polar-cap blackouts, Type III absorption of cosmic radio noises, and satellite observations (e.g., Rothwell and McIlwain, 1959, Reference 195). The curve labeled (3) is due to Anderson et al. (1959, Reference 196) from balloon observations. Most other values mentioned by investigators lie between curves (2) and (3) for nonrelativistic events. Below 1 Mev, the curve (4) was obtained from observations of the hydrogen alpha auroral spectral lines (Chamberlain 1954, Reference 197). Curve (5) represents rocket observations of auroral particles (protons). (See Van Allen, 1958, Reference 198 and Meredith et al., 1958, Reference 199).

The label "auroral particles" attached to curves (4) and (5) implies only that these proton fluxes were calculated from observations in or near aurorae. It is believed that the primary source of the luminosity of aurorae is electrons incident on the upper atmosphere, and electron fluxes are not presented in Figure 26. The curves (4) and (5) give proton fluxes contributing to the environment over the auroral zones, or about 60-80° geomagnetic latitude. For a long time the aurorae have been thought to be produced by the bombardment of the earth's upper atmosphere by high-speed particles ejected from the sun during periods of solar activity. Thus, auroral particles are included in Figure 26 as particles of solar origin. However, the manner in which these particles coming from the sun interact with the earth's magnetic field and finally make their way into the atmosphere to produce the aurora is unknown. It is possible that these soft-proton auroral fluxes are part of the geomagnetically trapped radiation, in which case they will be observed within a belt bounded very roughly by the 60 to 80° geomagnetic field lines.

III Radiation and Space Debris Hazards, C (cont.)

Also presented in Figure 26 are the vertical atmospheric-penetration depths due to Bailey (1959, Reference 193) and magnetic cutoffs for an ideal geomagnetic dipole.

The condition, whether particles entering the geomagnetic field behave like a single particle or a conducting plasma, is indicated by the dotted line, cutting across Figure 26 (Ferraro, 1952, Reference 200). This limit for plasma behavior crosses over the spectrum of solar particles at the 1 to 100 Mev range. Therefore, above this range, solar particles can be treated as independent particles while, for particles significantly below this limit, the interparticle electromagnetic interactions become important.

The time decay of the high-energy end of the solar-flare spectrum typically follows the form t^{-n} , where n varies between 1.5 and 3. However, because of the existing dispersion, these decay laws should not be applied to the entire solar-flare spectrum, and it is generally unreliable to extrapolate observed fluxes backward in time using a t^{-n} decay in order to estimate maximum expected fluxes. A schematic of what must occur in the time development of the solar-particle spectrum at the earth is shown in Figure 27.

Spectral measurements by other investigators give results lying between curves (1) and (2) of Figure 26 for relativistic solar particles and between curves (2) and (3) of Figure 26 for nonrelativistic solar particles. For example, K. A. Anderson and D. C. Enemark (1950, Reference 201) give the following spectrum including the time dependence from observations on 15 July 1959:

$$\left\{ \begin{array}{l} 85 \text{ Mev} < E < 300 \text{ Mev} \\ t > 1 \text{ to } 2 \text{ days} \\ n(E, t) = \frac{15 \times 10^{10} t^{-3} E^{-4}}{\text{cm}^2\text{-sec}} \end{array} \right\}$$

III Radiation and Space Debris Hazards, C (cont.)

However, Van Allen (1961, Reference 202), using data from Explorer VII following the flare of 12 November 1960, found intensities as high as 2.4×10^4 particles/cm²-sec for $E > 30$ Mev, and a time integral of this intensity for 12-16 November of $\sim 10^9$ particles/cm². This is somewhat higher than curve (2) of Figure 26. For the same flare, Wasson (1961, Reference 203) calculated intensities agreeing with Van Allen (1961, Reference 202) from the production of radioactive Ag¹⁰⁶ in an emulsion block carried by Discoverer XVII. Also, Winkler et al. (1961, Reference 204) reported a proton flux of 1.5×10^7 particles/cm²-sec for $E > 40$ Mev, obtained by extrapolating a balloon measurement to free space. Winkler et al. (Reference 204) regard this value as highly uncertain.

In conclusion, the integral intensities of solar cosmic rays indicated in Figure 26 are considered fairly reliable, but intensities of non-relativistic solar-flare protons possibly can reach values as high as 10^4 particles/cm²-sec for $E > 20$ Mev, on some occasions. It seems probable, however, that fluxes this high have never actually been observed. The intensities presented apply to solar-particle beams with little or no geomagnetic cutoff effects included. They apply to free space and regions over the polar caps. For regions near the earth at low latitudes, the spectrum observed is cut off at higher energies to an extent which depends on geomagnetic activity.

6. Prediction of Flares

The extent to which it is possible to predict the occurrence of solar flares producing the more intense proton-beams is currently being investigated. The present status of these studies is indicated by Robey, (1961, Reference 205) and K. A. Anderson and C. E. Fichtel (1961, Reference 206). No quantitative formulas for predicting the occurrence of flares exist, but long-range studies give estimates of conditions to be expected over long periods during the solar cycle. Also for short-duration trips of less than one week, favorable launching dates can be recognized.

III Radiation and Space Debris Hazards (cont.)

D. PRIMARY COSMIC RADIATION

The primary cosmic radiation evidently fills interstellar space as an isotropic flux of high-energy particles, mostly protons. Eighty-five percent of the primary particles are hydrogen, 14% helium, approximately 1% are in the carbon-nitrogen-oxygen group, and 0.25% in the group heavier than neon. There is a small flux of lithium, beryllium, and boron which is approximately 0.25% of the total flux. It is presently believed that high-energy electrons and gamma rays constitute less than 1% of the total flux.

A few of these primary cosmic particles possess energies as high as 10^{18} electron volts. The cosmic-ray integral spectrum is indicated in Figure 26, but near the earth a strong latitude effect is introduced by the geomagnetic field. Incoming particles are deviated toward the east and may be completely deflected by the geomagnetic field before reaching the top of the atmosphere. The minimum energy of a vertically incident particle able to reach the top of the atmosphere at a particular geomagnetic latitude is called the geomagnetic cutoff energy at that latitude. For protons this is indicated in Figure 26.

The flux of cosmic rays is not constant; the two most important types of modulation are the 11-year solar-cycle variation and the Forbush or magnetic-storm decrease. Above 20 Bev/nucleon the cosmic-ray intensity is steady in time to within $\pm 2\%$. Below 20 Bev/nucleon the cosmic-ray intensity follows the 11-year solar cycle, being higher at times of solar minimum. Presumably when the sun is inactive the cosmic rays reach the earth unhindered, and when the sun is active it sweeps back the cosmic rays with its magnetic field, thereby excluding low-energy particles from the vicinity of the earth. However, none of the proposed mechanisms for modulating the primary cosmic-ray intensity appear to fit the experimental data.

The total flux of cosmic rays for energy greater than 1 Bev is 0.2 particles/cm²-sec-ster at sunspot maximum. The energy density is approximately

III Radiation and Space Debris Hazards, D (cont.)

1 ev/cm^3 compared to about 0.05 ev/cm^3 for starlight (Reference 207). The details of the integral spectrum over the range 0.15 Bev - 10^{10} Bev for primary cosmic rays near sunspot maximum is given in Table 16 (Singer, 1958, Reference 208, and Noon et al., 1957, Reference 209). The total intensity is decreased by a factor of about 2 from solar minimum to solar maximum and the lower-energy particles are affected most (McDonald and Webber, 1960, Reference 210). Therefore, the total flux of particles of energy greater than 1 Bev can be expected to be about $0.4 \text{ particles/cm}^2\text{-sec-ster}$ at sunspot minimum. The shielding of cosmic-ray primaries is not a rewarding operation because of the very high penetrating characteristics of these relativistic ions.

Even with generous allowances for the high relative biological effectiveness of heavy particles, the estimated integrated dose delivered to an unprotected man in space would be on the order of only $1/2 \text{ rem}$ (roentgen equivalent man) per week, and is therefore of negligible effect except for journeys of several years. The galactic cosmic radiation will have essentially no effect on materials, except for certain photographic emulsions.

E. METEOROID ENVIRONMENT

A meteorite is a solid body which is known as a meteoroid when in an astronomical orbit and as a meteor when it strikes the earth's atmosphere. The smaller meteorites, or those weighing less than about 10^{-3} grams, are called micrometeorites and are often referred to as dust particles or the dust component. The entire mass-spectrum of meteorites is also sometimes referred to as dust, or cosmic dust, or interplanetary dust, because the particles are mainly micrometeorites. The composition, size, mass, density, velocities, spatial distribution, and number density of meteorites near the earth are known only within rather wide limits, and there is much disagreement about conclusions to be drawn from available measurements. This is especially true for the more numerous dust particles observable only from space probes and satellites.

Much of our knowledge of meteorites near the earth is based on observations by optical and radio reflection techniques of physical phenomena occurring during the interaction of these bodies with the atmosphere. Study of

III Radiation and Space Debris Hazards, E (cont.)

the remnants of meteors and material of meteoric origin, such as magnetic nickel-iron spherules in deep-sea sediments, has provided additional information. More recently, micrometeorites, which are too small to produce meteoric phenomena observable by radar, visual, or photographic techniques, have been detected by means of devices carried in rockets, earth satellites, and other spacecraft. The dust-particle sensors that have been flown have necessarily been of simple design, primarily giving preliminary information about the influx rate or spatial density of dust particles over a limited range of particle mass. More sophisticated experiments capable of defining selected parameters of individual dust particles undoubtedly will be performed in the near future.

In addition to ground-based observations of meteoric phenomena and direct observations by rocket- and space-borne sensors which give information on meteorites near the earth, photometric studies of the zodiacal light and the solar corona involving light-scattering by dust particles give information on the interplanetary dust distribution far from earth. From all these observations, meteorites may be provisionally divided into two classes: those of asteroidal origin, and those of cometary origin (Reference 211).

1. Meteorites of Asteroidal Origin

Meteorites believed to be of asteroidal origin occasionally reach the surface of the earth. They are primarily stony fragments having a density of from 3 to 3.5 g/cm³, but about 10% are iron-nickel fragments with densities of from 7 to 8 g/cm³. Their masses are often above 1 g. Their orbits around the sun are, for the most part, circular and in or near the ecliptic plane. Their direction of revolution is direct - that is, the same as the earth's. Their velocities relative to the earth are usually around 20 km/sec, although occasionally an asteroidal meteorite may have a relative velocity as high as 72 km/sec, which is the maximum velocity for a head-on collision with the earth of a body in orbit around the sun. There are relatively few asteroidal meteorites around the earth but their concentration probably increases considerably toward the asteroidal belt between the orbits of Mars and Jupiter. Near the

III Radiation and Space Debris Hazards, E (cont.)

earth's orbit, at least, the flux is so low that they do not constitute a hazard to spacecraft (References 212 and 213). Because of this fact, in the following discussions the unqualified term "meteorite" or "meteoroid" will refer only to those of nonasteroidal origin.

2. Meteors of Cometary Origin

a. General Characteristics

These meteorites are observed both directly by means of instruments aboard spacecraft and by means of radar or visual and photographic ground-based observation; there is also the additional effective technique of photometric studies of zodiacal light and the solar corona.

The conventional description of the meteoroid population holds that there are a few streams of particles which cause meteor showers when intercepted by the earth, plus a large background of "sporadic" meteoroids traveling almost independently, but which still show groupings. Most meteoric material in the solar system is believed to be associated with existing or extinct comets, and perhaps 1% of the photographic or smaller meteors are of asteroidal origin in the vicinity of the earth. Thus the distribution originated from typical comet orbits about the sun, modified by the effects of sputtering, sublimation from solar radiation, breakage and disruption by mutual collisions among the small particles themselves, planetary perturbations and encounters, light pressure, and solar-radiation drag (Poynting-Robertson effect). These effects result in the elimination of material from the interplanetary medium by expulsion from the solar system, collisions with planets, and solar capture. This description has developed from observations of radio, visual, and photographic meteors, and seems to apply to meteorites with masses greater than about 10^{-4} g. For example, radar-observed meteor velocity-distributions lie in the 11 to 72 km/sec range which is required for particles orbiting the sun, and orbit calculations based on photographic observations indicate that the vast majority of visual meteorites are in solar orbits. The orbits are elliptical, mostly with high eccentricities, and lie at all angles to the ecliptic plane. Most

III Radiation and Space Debris Hazards, E (cont.)

are in direct low-inclination orbits, but some are in retrograde motion opposite to the earth). Meteorites large enough to be visible on entering the atmosphere show no concentration near the earth. Their velocities relative to the earth average about 30 km/sec.

Those particles associated with "showers" move together in elliptic orbits which the earth may intersect once or twice a year. In some cases these meteoroids are almost uniformly distributed along their orbit, and in others they are concentrated near one point in the orbit so that high fluxes are encountered by the earth only once in many years. Shower fluxes are commonly about 10 times (but may range up to 10^5 times) the normal sporadic background. These fluxes last from a few hours to a few days; the mass distribution in a shower differs from that of the sporadic background and from other showers. The age of a meteor stream seems to have a major effect on its mass distribution. Since a concentration of dust particles will rapidly be dispersed by the Poynting-Robertson effect and by the cumulative effects of small differences in the orbital elements of individual particles, it seems plausible that younger streams are more likely to contain small dust particles than are older streams. It also seems reasonable that very young meteor streams are more likely to contain concentrations of meteoroids. When a meteor shower occurs, the direction in the sky from which a meteor appears to come is called its radiant. The average deviation of photographic-meteor radiants from the mean radiant of the stream is used as a measure of the age of the stream.

Densities derived from observation of photographic meteors indicate a rather porous structure and range from 0.01 to 1 g/cm^3 , depending on "reasonable" estimates of luminous efficiencies. Whipple (1963, Ref. 173), using improved luminous efficiency measurements from the Trailblazer I (analyzed by McCrosky and Soberman, 1962, Ref. 228) and by independent determinations (from three asteroidal meteors by Cook, Jacchia, and McCrosky, Ref. 229), concludes a meteoroid density of 0.44 g/cm^3 .

III Radiation and Space Debris Hazards, E (cont.)

Deceleration measurements on photographic meteors have also indicated a porous, lacy structure of low density for particles fainter than about magnitude 0. Verniani (1961, Reference 214) has recently calculated the density of photographic meteors, most of which were fireballs, using Whipple's older data and ablation theory with the following results: about 44% had a density of 3.38 g/cm^3 , 35% were porous bodies with an average density of 0.67 g/cm^3 , and 21% were dustballs with an average density of 0.15 g/cm^3 . Collection of small particles in a rocket-borne device (the "Venus Flytrap" equipment) also indicates low-density, weak structures (References 215 and 216). These densities and types of structures observed are consistent with the cometary-origin hypothesis.

It is generally believed that micrometeorites belong to the same population as the particles which cause the meteoric phenomena studied by ground-based techniques. Therefore, the concepts of meteoroid characteristics gained from the study of larger particles of mass greater than about 10^{-5} g have generally been applied also to the micrometeorites. They are assumed to be in heliocentric orbits with masses ranging upward from a lower limit set by solar radiation pressure of about $4 \times 10^{-10} \text{ g}$ for a density of 0.05 g/cm^3 and about $7 \times 10^{-14} \text{ g}$ for a density of 3.5 g/cm^3 . At the upper end, micrometeorite masses approach the masses of those which cause radio meteors. Flux intensities for radio and photographic meteors as a function of mass have been extrapolated to the micrometeorite range. Micrometeorite orbits are probably nearly circular and are near the plane of the ecliptic. It is likely that most are in direct, rather than retrograde, orbits. For direct orbits the velocities relative to earth are mostly under 20 km/sec, while for retrograde orbits the velocities may approach 60 km/sec.

It is thought that smaller particles of cometary origin would be of greater density than the larger ones and that the density of the smallest particles would approximate that of stone. Thus, a density of about 3 g/cm^3 is often assigned to those particles of mass less than about 10^{-4} g .

III Radiation and Space Debris Hazards, E (cont.)

This belief is based on the assumption that, in the formation of cometary material, the condensation of the less volatile materials occurred first, with later condensation and accumulation of the more volatile "ices." However, the "Venus Flytrap" experiment mentioned above (Reference 216) suggested that low-density weak structures were still prevalent among particles with dimensions on the order of microns.

Predictions have been made, on theoretical grounds, of increased dust concentration around the earth by both American (References 217, 218) and Russian writers (Reference 232). Recently, Whipple (1961, References 215, 219, and 233), has also proposed that the flux intensity of dust particles decreases with altitude above the earth until an interplanetary value is reached and that this dust cloud originates by means of meteoroid impacts on the moon which expel material in cislunar orbits. Whipple bases the altitude dependence of micrometeorite flux on an analysis of satellite data. Hibbs (1961, Reference 220), using only Explorer I data, had previously suggested an altitude dependence and also claimed that his analysis showed that the particles which impacted on Explorer I were probably in earth orbits. Dubin (1961, Reference 221) raised several objections to Hibbs' work, which Hibbs appears to have adequately explained (1961, Reference 222). An interpretation of the satellite data in addition to the dust-cloud theory has also been proposed; it assumed that the flux intensity as a function of mass is increasing for smaller particles to a greater extent than that previously supposed. This interpretation is supported by Explorer VIII data which was not included in Whipple's dust-cloud analysis. Other experimental data substantiating the near-earth dust cloud are presented in paragraph III, E, 2, b below.

A high degree of uncertainty exists as to the proper interpretation of available meteoroid observations. In the case of optical and radar observations, the directly measurable quantities are luminous intensity, radio ionization, and number and velocity of particles. Masses and densities

III Radiation and Space Debris Hazards, E (cont.)

must be theoretically derived, and the physics of the interaction of meteoroid and atmosphere is not well known. The threshold sensitivity of acoustical detectors carried aboard spacecraft is functionally related to the mass and velocity of the striking particle, but it has not been possible to establish this relationship with certainty for the high velocities characteristic of meteoroids. More observations of varied types, with greater experimental control, must be made by space probes and satellites before present uncertainties in regard to velocities, densities, and spatial distribution of meteorites can be resolved.

There is also a nearly complete gap in observational data on meteorites in the range from 10^{-5} to 10^{-7} g. Knowledge of particles of this size is important in studying penetration problems of space vehicles. Particles smaller than about 10^{-6} g are easily stopped and present no penetration problem, whereas particles larger than about 10^{-3} g occur too rarely for consideration. Extrapolation from radio and optical data for flux-intensity values are usually applied to meteorites in this range.

b. Results of Measurements

With the above perspective, the main features of the meteoroid environment are presented in Figures 28 through 30 and Tables 17 through 20.

Figures 28 and 29 summarize present data on flux intensities of meteorites as a function of meteorite mass in the range of interest. The flux for a given mass is the number of particles with a mass greater than the given value which cross $1 \text{ m}^2/\text{sec}$ of a surface element. It is given for 2π steradians and counts particles coming from one side only. The uncertainty in determining the mass of a zero-magnitude meteor results in the spread indicated by the lines labelled $m_0 = 1 \text{ g}$ and $m_0 = 30 \text{ g}$ in Figure 29 for the flux of photographic and radio meteors. Whipple has assigned the range 1 to 30 g, and first suggested a preferred value of 25 g, for the zero-magnitude particle but has more recently (1963) revised the preferred value to 1 g.

III Radiation and Space Debris Hazards, E (cont.)

The satellite data are obtained as recorded impacts per unit area per unit time above the mass threshold sensitivity of acoustical detectors. The latter has been obtained by assuming a linear dependence of the detector response on the momentum of the striking particle and taking 30 km/sec as the average meteorite velocity when the spacecraft was not oriented or when the dust particle sensors are open to an omnidirectional flux. Average velocities for oriented sensors were chosen according to the orientation of the solid viewing angle of the sensor. Calibration was performed with particles ranging from glass beads, impacting elastically at low speeds, to small iron spheres inelastically impacting at speeds up to about 10 km/sec.

A summary of meteorite information based on photographic and radar data is given in Table 17, prepared by Whipple (1958, Reference 223). It assumes that a zero-magnitude meteor has a mass of 25 g and that the magnitude and mass are related by the formula $M = 2.5 \log_{10} m_0/m$, where M is the magnitude, m is the meteor mass, and m_0 is the mass of a zero-magnitude meteor. The flux values are for all particles with masses greater than the given mass. The values in the last column are for 4π steradians, and those in the next-to-last column assume a 50% shielding by a planet. Whipple assigned different values of average velocity to different sizes of dust particles. The velocities assigned varied from 28 km/sec for the visual meteorites to 15 km/sec for small dust particles of the direct-measurement size range.

Parameters of the most important meteoroid streams are given in Table 18 (Vedder, 1961, Reference 224). Since each shower normally recurs annually, the dates are also given. The mass spectrum probably varies considerably with different meteoroid streams.

McCracken and Alexander (Reference 225) have discussed the distribution of micrometeorites in the vicinity of the earth as directly measured by microphone systems carried by rockets, satellites, and space probes. The available direct measurements that have been obtained from these systems are shown plotted in Figure 28. Many of the following comments are adapted or quoted directly from this discussion.

III Radiation and Space Debris Hazards, E (cont.)

The data obtained using microphone systems are entirely sufficient to establish an average distribution curve for interplanetary dust particles in the vicinity of the earth. Except for Explorer VIII, which is discussed separately below, American satellites and spacecraft for which direct measurements have been obtained are listed together with relevant data in Table 19 (Reference 225). No correction was made for the shielding effect of the earth on Pioneer I, which spent most of its time at large geocentric distance.

Analysis of telemetered data from Vanguard III has not yet been completed; thus the results shown in Table 19 may change slightly. An average particle velocity of 30 km/sec was used in computing the threshold mass sensitivities for the microphone systems for the spacecraft listed in Table 19.

Direct measurements from the microphone systems mounted on Soviet satellite and spacecraft are given in Table 20 (Reference 225). Corrections are not made for the shielding effect of the earth for measurements made at large geocentric distance.

A definitive set of direct measurements recently was obtained by means of the Explorer VIII satellite (Nov.-Dec. 1961; see Figure 28). The three datum points obtained with the Explorer VIII microphone system are corrected for the shielding effect of the earth and represent the impacts of more than 3100 micrometeorites registered during an interval of 40 days. An average particle velocity of 25 km/sec was assigned in obtaining detector mass sensitivity until the velocity distribution of dust particles can be determined. The three Explorer VIII datum points establish the shape of a segment of an average distribution curve that extends over approximately three orders of magnitude in particle mass.

McCracken and Alexander (Reference 225) have this to say: "The two interpretations of direct measurements that could be given prior to obtaining the new direct measurements from Explorer VIII (1960 Xi) were:

III Radiation and Space Debris Hazards, E (cont.)

(1) the mass distribution and spatial density of small interplanetary dust particles indicated by the direct measurements differ significantly from those which have been predicted on the basis of linear extrapolations (over about six order of magnitude) of results from observations of meteors; or (2) the direct measurements indicate the existence of an appreciable geocentric concentration of interplanetary dust particles. The conjectural geocentric concentration mentioned here is of the type proposed by Beard (1959, Reference 217) and should not be confused with concentrations arising from the temporary suspension of dust particles above the temperature-inversion layers in the atmosphere of the Earth.

"The direct measurements obtained with Explorer VIII strongly indicate that the first of the two interpretations of the presently available direct measurements is the correct one. The second interpretation is not compatible with an analysis in which the direct measurements from Explorer VIII are used as a basis for analyzing other direct measurements. The first interpretation should, therefore, be regarded as the correct one until direct measurements of the vectorial velocities of impacting dust particles have been obtained. The direct measurements from Explorer VIII serve as the first firm basis for analyzing all existing direct measurements of interplanetary dust particles. A review of all the available direct measurements (including those from Explorer VIII) obtained with microphone systems is sufficient to demonstrate the validity of the foregoing statements about the interpretation of the direct measurements."

Using data from Explorer I, Sputnik III, Vanguard III, Explorer VI, and Pioneer I, Whipple (1961, References 215 and 219) has derived an altitude dependence for flux intensities for the mass threshold of 10^{-9} g. This assumes a straight-line function of log-flux vs log-mass, which is strongly indicated by Figure 29, if Explorer VIII data points are eliminated. The deviations from the straight line are then assumed by Whipple to be due to altitude differences and plotted against the altitude. Whipple's results indicate that a distance of about 10^5 km the concentration falls off roughly

III Radiation and Space Debris Hazards, E (cont.)

as the inverse 1.4 power of the distance from the earth's surface. Whipple ascribes the apparent dust cloud to the impact on the moon of meteoric bodies of cometary and asteroidal origin at high velocities (up to 72 km/sec), with ejection of dust and droplets. A portion of this dust is assumed to be ejected into cislunar (earth) orbits. The higher concentration near the earth would be caused by convergence of the orbits and atmospheric drag effects.

Measurements from the Midas II, Pioneer I and Vanguard III (taken from Soberman and Della Lucca, Reference 232) together with the Explorer VIII data show the flux dependence on altitude, Figure 30. Russian satellites show similar results, excepting that the largest concentration is interpreted to be 100-300 km above the earth's surface (Reference 233).

T. N. Nazarova, using more extensive data obtained in the USSR, supports the basic concept of the dust belt, but postulates a slower fall-off (Nazarova and Moroz, 1961, Reference 226); Hibbs (1961, Reference 220), from a statistical analysis of Explorer I data, concluded that an altitude dependence was indicated to a 90% confidence level. However, the data was insufficient to quantitatively relate flux of particles and altitude in a convincing way.

The Mariner II data have shown four orders for magnitude of difference between near-earth and interplanetary environments. Only two impacts were recorded by the Mariner II during 109 days of flight, as compared to 3,700 impacts in one month by an earth satellite. (However, recent Explorer XVI data, 1963, Reference 234 and 235 show a very low impact rate. About 24 accumulated punctures were recorded in 2.5 months, 16 December 1962 thru 1 March 1963; this result is somewhat confusing and in general disagreement with other satellite data.)

The concept of a dust cloud has not been applied to the larger particles. In particular, it has not been applied to particles relevant to penetration problems (from 10^{-3} to 10^{-7} g).

III Radiation and Space Debris Hazards, E (cont.)

The direct measurements listed in Tables 19 and 20 encompass a variety of altitudes, sensitivities, lengths of sampling interval, and times of the year. The fact that all except the direct measurement from Pioneer I fit the distribution curve established by Explorer VIII leads substantial support to the validity of the distribution curve shown in Figure 28 as an average distribution curve that can be used until more sophisticated experiments have established the distribution curve over a considerably larger range of particle mass.

McCracken and Alexander (Reference 225) go on to say:

"There are uncertainties encountered in displaying the direct measurements as a mass distribution. It is quite advantageous to the present analysis to point out these uncertainties. Qualitative discussions of the uncertainties are followed by attempts to assign numerical values to the uncertainties.

"The values of average particle velocity assigned in converting from momentum sensitivity to mass sensitivity for the systems may be slightly too high. The correct values depend on the velocity distribution that exists for dust particles in the direct-measurements range of particle size. Lower average particle velocities would apply if most of the dust particles were in geocentric orbits or direct circular heliocentric orbits. The use of lower particle velocities would tend to shift the direct measurements toward slightly higher values of particle mass without markedly changing the shape of the distribution curve. Even a radical reduction from about 30 km/sec to the value of 15 km/sec used by Whipple would lower the threshold mass sensitivities by only a factor of two.

"The impulse delivered to a sensor as a dust particle impacts at hypervelocity is almost certainly greater than the impact-momentum of the dust particle, but remains unknown. A value greater than unity (which is used in Table 19 and 20) for the ratio of the impulse to the impact-momentum increases the momentum sensitivities for microphone systems. The proper correction factors probably lie between 2 and 3 and are now (Fall 1961) being established by hypervelocity accelerators.

III Radiation and Space Debris Hazards, E (cont.)

"Allowing for the impacts of dust particles at angles of incidence appreciably different from 90° effectively decreases the momentum sensitivity, but the decrease is probably less than a factor of two. This uncertainty can be largely removed through the use of more directional sensors.

"The magnitude of the correction for the shielding effect of Earth depends on the velocity distribution of the dust particles. The corrections that have been applied involve the assumption that the dust particles are predominantly in heliocentric orbits and are not necessarily confined to direct circular orbits. If this assumption is not valid, then slightly smaller corrections for the shielding effect of Earth would be applied. The factors applied to correct for Earth's shielding of the spacecraft were all less than or equal to 2. Use of smaller correction factors than were used would shift the direct measurements toward slightly lower values of influx rate without changing the shape of the distribution curve.

"Knowing which of the minor corrections to apply requires a better knowledge than exists at present of the mass distribution, velocity distribution, and spatial density of the interplanetary dust particles. All of the direct measurements have been handled in as consistent a manner as possible, so that introducing minor corrections will change only the position of the direct measurements on a plot of mass distribution without changing the shape of the distribution curve. It seems reasonable to assume that likely combinations of the minor uncertainties will leave the distribution curve as it is shown in Figure 28. Direct measurements obtained at large distances from Earth and/or a determination of the velocity distribution are needed before much further progress can be made in defining a model distribution of the interplanetary dust particles.

"The distribution curve shown in Figure 28 can only be used to describe average conditions. It is already known from the direct measurements that fluctuations in the influx rate of at least ± 10 occur within intervals of a few hours for particles with masses of approximately 10^{-10} g. The magnitude of the fluctuations presumably becomes quite large for particles

III Radiation and Space Debris Hazards, E (cont.)

near the radiation pressure limit on particle size. The distribution curve is slightly biased toward the autumn of the year because of the distribution in time of year of the direct measurements. If the annual variation in influx rate of dust particles resembles that of meteors, then the curve shown in Figure 28 represents influx rates that are slightly higher than the true average values.

"Large inconsistencies have been attributed to the direct measurements several times in the literature (Whipple, Reference 215). The various direct measurements seem to be remarkably self-consistent when analyzed on the basis of the new direct measurements from Explorer VIII. The authors place much confidence on the direct measurements from Explorer VIII. The reliability, calibration, and reasons for assigning a high level of confidence to the Explorer VIII measurements are being published in greater detail.

"The micrometeorite distribution curve shown in Figure 28 can be well approximated by a straight-line segment with the equation

$$\phi = 10^{-17} m^{-1.70}$$

where ϕ is the hemispherical flux intensity (per m^2 -sec- 2π ster) in number of particles with mass m or greater, and m is in grams. Caution must be used in extrapolating this distribution curve out of the range of particle mass for which direct measurements have actually been obtained. The above distribution ϕ holds approximately for m in the range 10^{-10} to 10^{-6} g, and is applied for an average velocity of 30 km/sec. It should be emphasized that the portion of the distribution curve defined in this range by Explorer VIII departs significantly from straight-line extrapolations from radar and photographic data. (For example, compare Whipple's extrapolation for $m_0 = 30$ g with Explorer VIII points in Figure 28.) The new distribution curve supports the theory that the flux intensity as a function of mass increases very rapidly for masses below approximately 10^{-7} g." (Also see Whipple, 1961, Reference 215.)

III Radiation and Space Debris Hazards, E (cont.)

It is obvious that calculations based on these data may be in error by an order of a magnitude or more. The lack of extensive data, combined with the time variability of particle fluxes, reduces the reliability of the satellite data, whereas the difficulty of accurately relating magnitude to mass introduces much uncertainty in the values obtained by radio and photographic techniques. For calculations, a straight-line approximation of log-flux vs log-mass is desirable, apart from whatever the actual dependence may be. It has been customary to approximate the entire spectrum including the satellite data by the formula

$$\phi = 10^{-12} m^{-10/9}$$

where ϕ is the flux intensity in number of particles with mass m or greater per m^2 -sec (e.g., Bjork, 1961, Reference 171). This formula fits the satellite data previous to Explorer VIII very well if statistical considerations are taken into account. With the new data of Explorer VIII, the new straight-line approximation $\phi = 10^{-17} m^{-1.70}$ with increased slope is indicated for the range of particles of mass less than about 10^{-6} g, or, in other words, for particles significant in considerations of surface-erosion effects as contrasted to those concerning penetration. No reason now seems to exist for attempting to approximate the entire spectrum by one straight line; for purposes of calculation, where a straight-line dependence is sufficient and desirable, the satellite data should be used for one approximation valid below about 10^{-6} g, and radar and photographic data should be used to derive another approximation valid above about 10^{-4} g. Whipple's data (Table 17) should not be used in the region below 10^{-4} g. Even in the visual region, Whipple's data are lower than some other estimates. Hawkins and Upton (1958), from an extensive study of visual and photographic meteors, give the flux intensity as

$$\phi = 6.4 \times 10^{-13} m^{-4/3}$$

 III Radiation and Space Debris Hazards, E (cont.)

where ϕ is the number per m^2/sec and m is the minimum mass in grams. This applies only in the region below about 10^{-1} g. In this region, this approximation and the one given above ($\phi = 10^{-12} m^{-10/9}$) agree very well.

The flux intensity in the region of primary importance for penetration calculations (10^{-3} to 10^{-6} g) must, at present, be obtained by extrapolation to larger masses from satellite data or to smaller masses from radio and photographic values. In addition, the meteor streams, many parameters of which are given in Table 18, must be considered in estimating fluctuations in penetration hazards.

It is somewhat difficult to join smoothly the new distribution curve defined by Explorer VIII to the radar and photographic data; however, the curve labelled $m_0 = 30$ g in Figure 28, e.e., the curve assigning a mass of 30 g to a zero-magnitude meteor may arbitrarily be taken as a conservative estimate of the average flux in the range from 10^{-3} to 10^{-6} g for use in penetration calculations. This curve in Figure 28 is given approximately by the formula:

$$\phi = 1.28 \times 10^{-12} m^{-1}$$

In 1963, Whipple (Reference 173) revised his previous work suggesting a slope of -1.34 (very close to Hawkin's and Upton's value) but at a different location on the mass-flux graph. Whipple (1963) suggests the following numerical expression for his 1963 curve (Figure 29), which he considers a "pessimistic" estimate:

$$\log \phi = -1.34 \log m + 2.68 \log (.443/\rho) - 14.48$$

Correspondingly, Whipple revises the older Watson law, which he describes as "optimistic," as being:

$$\log \phi = \log m + 2 \log (0.443/\rho) - 13.80$$

III Radiation and Space Debris Hazards, E (cont.)

To summarize: For the purpose of environmental calculations, the flux $\phi = 10^{-17} \text{ m}^{-1.70}$ represents well the range from 10^{-10} to 10^{-6} g; $\phi = 1.29 \times 10^{-12} \text{ m}^{-1}$ can be used very conservatively for meteorites of mass greater than 10^{-3} g in estimating penetration hazards. Whipples most recent comprehensive value, generally considered to represent the latest analysis for use in penetration estimates, is $\log \phi = -1.34 \log m + 2.68 \log (.443/\rho) - 14.48$.

Since no adequate data presently exist on the altitude dependency of flux in the mass ranges of interest for penetration (10^{-3} to 10^{-6} g), it is recommended that the concept of a geocentric dust cloud should, at present, not to be used in these mass ranges.

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plates show that the amount of water vapor is too small to support the Sagan greenhouse theory. It is shown that the amount of water vapor to the total atmosphere (ratio) is 9×10^{-7} by mass. Spinrad concludes that the greenhouse effect may be due to molecular absorption other than water.

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A short article covering the May COSPAR meeting in Washington, D.C. discussing the radar measurements obtained from the Goldstone transmitter by Victor and Stevens. It is inferred from these measurements that the surface roughness and composition of Venus may be similar to that of the earth.

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56. L. D. Kaplan, A Preliminary Model of the Venus Atmosphere, Technical Report No. 32-379, Jet Propulsion Lab., Dec. 12, 1962.

"Standard" and extreme model atmospheres of the planet Venus are calculated with temperature, density, and pressure given as functions of height. Use is made of the Spinrad total pressure and rotational temperatures, (based on Dunham's CO_2 spectra), the occultation of Regulus, and a surface temperature of $700^{\circ}\text{K} \pm 140^{\circ}$, (originally from radar data but in good agreement with Mariner II results).

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An excellent discussion of the status of Venus as of late 1961 presenting various opposing theories and evaluations and reviewing pertinent data. Experiments to distinguish among the alternative models are discussed. Several appendices are included: "The General Circulation of Planetary Atmospheres," by Mintz, "Interpretation of the Near-Infrared Bands of Venus," by Chamberlain, and others.

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62. L. D. Kaplan, "The Structure and CO₂ Content of the Venus Atmosphere," Astronomical Journal, September 1961.
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63. A. E. Lilley, "The Temperature of Venus," Astronomical Journal, September 1961.
Substantial new evidence for high surface temperature of 600°K is presented based on measurements at wavelengths of 21 cm.
64. Carl Sagan, "On the Origin of the Venus Microwave Emission," Astronomical Journal, March 1961.
Theoretical models are proposed to account for the apparent change in brightness temperature from 600°K to about 300°K with wavelength. The low surface temperatures are shown to be inconsistent with the greenhouse effect. The likelihood of a 1 gauss magnetic field is also mentioned.
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With radiative equilibrium the atmosphere is shown to be convectively stable and a mean temperature of 235°K. The circulation system is inferred from the appearance of the Venus clouds in visible and ultraviolet light. Mintz infers that the different appearance in the visible and ultraviolet may result from the fact that different levels are being observed; he suggests a possible way in which a symmetrical circulation regime centered on the sub-polar point at lower levels could change to a different centered circulation at high levels.
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68. A. H. Barrett, "Microwave Absorption and Emission in the Atmosphere of Venus," Astrophysical Journal, Vol. 133, p. 281 (1961).
A model atmosphere is proposed assuming 75% CO₂, now thought to be unrealistic. However, the paper contains a comprehensive summary of radiometric data.
- 68A. B. Warner, "The Emission Spectrum of the Night Side of Venus," Monthly Notices of the Royal Astronomical Society, Vol. 121, No. 3, p. 279 (1960).
The measurements given by Kozyrev of features in the spectrum of the night side of Venus are examined. The existence of nitrogen bands is confirmed, and evidence is presented identifying emission lines of neutral and ionized oxygen.
69. E. J. Öpik, "The Aeolosphere and Atmosphere of Venus," J. Geophysical Research, 1961.
The aeolosphere concept of the Venus atmosphere is described in rejecting the greenhouse effect. The aeolosphere model assumes the yellowish clouds to be dust kept in motion by high-velocity winds. Since the stirred up atmosphere will maintain an adiabatic lapse rate, the temperature will increase with increasing depth below the cloud tops, reaching the high surface temperatures observed by radio measurements.
70. Zdenek Kopal, "Aerodynamic Effects in Planetary Atmospheres," Aerospace Engineering, December 1960.
A brief summary of the physical and chemical characteristics of Mars and Venus are presented. With reference to Venus, Kopal states that the atmosphere is probably made up mainly of molecular nitrogen and only a small amount CO₂. This was the first mention found in the open literature. Kopal cites analysis which indicates that Venus might have a magnetic field of 1 to 2 gauss but warns that this result is by no means conclusive.

71. J. Strong and W. H. Sinton, "Radiometric Observations of Venus," Astro-physical Journal, Vol. 131 p. 470 (1960).
With regard to Venus, measurements in the far-infrared (thermal) emission indicate an effective temperature of $234^{\circ}\text{K} \pm 10^{\circ}$. It is generally believed this reflects the temperature of a cloud layer somewhere in the atmosphere.
72. G. De Vaucouleurs, "Remarks on Mars and Venus," in The Exploration of Space, edited by Robert Jastrow, published by the Macmillan Co., 1960.
An excellent summary article comparing orbital and atmospheric information of Mars, Venus, and earth. The discussion pertains mainly to Venus. Measurements of Kozyrev on the spectral reflectivity and the spectrum of the dark side of Venus (Newkirk) are presented and discussed.
73. J. Strong, "Discovery of Water Vapor on Venus," La Nature (France), Vol. 3298, p. 61 (1960).
Absorption lines due to water vapor were identified from balloon observations. The abundance could not be accurately established from these data.
74. C. Sagan, "The Radiation Balance of Venus," Technical Report No. 32-34, Jet Propulsion Laboratory, Pasadena, California, 1960.
It is shown that a greenhouse effect could be responsible for the high surface temperature of 600°K . Opik (1961) criticizes this greenhouse theory primarily on the basis that sufficient water vapor has not been observed consistent with the proposed model.
75. D. H. Menzel, and G. De Vaucouleurs, "Results of the Occultation of Regulus by Venus," Nature, Vol. 188, p. 28 (1960).
A detailed discussion is given of the results obtained from visual, photographic, and photoelectric observations of occultation of Regulus made by teams of observers from Harvard College Observatory and the Smithsonian Astrophysical Observatory.
76. A. D. Kuz'min and A. E. Salomonovich, "Radio Emission from Venus in the 8-mm Bandwidth," Soviet Astronomy AJ, Vol. 4, p. 279 (1960).*

* Translated from Astronomical Journal (USSR), Vol. 37, p. 297 (1960).

The results measurement of radio emission from Venus at 8 mm, made at Lebedev Physics Institute are reported. The brightness temperature, following inferior conjunction, was $315 \pm 70^\circ\text{K}$. The temperature increased to $430 \pm 130^\circ\text{K}$ after conjunction.

77. J. D. Kraus, "Apparent Radio Radiation at 11-m. Wavelength from Venus," Nature, Vol. 186, p. 462 (1960).
It is shown that the quasi-coherent radiation reported earlier was not from Venus but was, in all cases, probably interference of terrestrial origin. References to these earlier reports of the burst-type radiation are included [in particular, see Nature, 178, 33 and 687 (1956)]. Recent work by Carr, et al. (1961, Ref. 67) failed to show any intense disturbances from Venus.
78. D. E. Jones, "A Microwave Radiometer Experiment from the Planet Venus," Technical Report 34-112, Jet Propulsion Laboratory, Pasadena, California, 1960.
The high brightness temperature of nearly 600°K measured in the centimeter region is generally considered to be that of the surface of the planet.
79. H. C. Urey, "The Atmospheres of the Planets," Handbuch der Physik Berlin, Springer-Verlag, Vol. 52, p. 363 (1959).
Chemical composition, temperature, structure, and evolution of the Venus atmosphere are considered based on the earlier CO_2 dominated environment at total pressures considerably lower than now believed to exist.
80. G. Newkirk, "The Airglow of Venus," Planetary and Space Science, Vol. 1, No. 1, p. 32 (1959).
Low-dispersion, high-speed spectra of the unilluminated portion of Venus show emission features, in agreement with Kozyrev's observations. Kozyrev's other emission bands are not corroborated by these spectra.
81. F. J. Heyden, C. C. Kiess, and Harriet K. Kiess, "The Spectrum of Venus in the Violet and Near-ultraviolet," Science, Vol. 130, No. 3383, p. 1195 (1959).
Observations of the spectrum of the planet Venus, show that a wide, continuous absorption band is present in the violet and near-ultraviolet. It is similar

- in structure to the strong absorption, reported by others, for gaseous nitrogen tetroxide. However, Su-Shu Hong (Dec. 1961, Publications of the Astronomical Society of the Pacific) demonstrates that the existence of nitrogen tetroxide cannot be substantiated by theoretical analysis at this time.
82. J. H. Shaw, and N. T. Bobrovnikoff, "Natural Environment of the Planet Venus," Ohio State University, AD 242-176, February, 1959.
An excellent summary of the environmental characteristic of Venus as understood up to 1959. Regions where knowledge is lacking are defined, and various theories proposed to fill the gap have been reviewed and compared. Attempts were made to estimate the probable environment in cases where the environment could not be definitely established.
83. J. v. Narayana, "Magnetic Fields of the Planet Venus" Kodiakanai Obs. (India) August, 1959.
The value of the magnetic field of Venus is calculated to be about 0.4 gauss based on statistical plots of the daily equivalent planetary amplitude. The rotation is computed to be 2 to 24 days.
84. J. E. Gibson and R. J. McEwan, "Observations of Venus at 8.6-mm Wavelength," Paris Symposium on Radio Astronomy. Stanford, Stanford University Press, 1959, p. 50.
Observations of Venus at 8.6-mm wavelength gave a brightness temperature of $410 \pm 160^\circ\text{K}$.
85. L. E. Alsop, J. A. Giordmaine, C. H. Mayer, and C. H. Townes. "Observations of Discreet Sources at 3-cm Wavelength Using a Maser," Paris Symposium on Radio Astronomy. Stanford, Stanford University Press, 1959, p. 69.
Observations of Venus at 3.37 cm are reported giving an apparent blackbody temperature of $575 \pm 60^\circ\text{K}$. These observations are not significantly different from observations made with the same reflector at 3.15 cm wavelength in 1956.
86. J. L. Raymond, "Thermodynamic Properties of the Atmosphere of Venus," Rand Corporation November, 1958.

Extensive computations and numerical analysis for the Venus atmosphere based on an assumed 100% CO₂ atmosphere. Mollier Chart for CO₂ is presented for temperatures up to 24,000°K and complete thermodynamic properties of the CO₂ were carefully computed including enthalpy, entropy, molecular weight, density, internal energy, and molecular composition.

87. C. H. Mayer, T. P. McCullough, and R. M. Sloanaker. "Observations of Venus at 3.15-cm Wavelength," Astrophysical Journal, Vol. 127, p. 1 (1958).
Radiation from Venus at 3.15-cm wavelength give the apparent blackbody temperature for Venus as about 560 $\pm$ 73°K.

88. I. K. Koval, "The Absolute Photometry of Venus in Ultraviolet and Infrared Light," Soviet Astronomy AJ, Vol. 2, p. 739 (1958).
The diameters of the image of Venus in ultraviolet and infrared light are shown to be equal. The cloud formation was 12% brighter than a symmetrical unclouded region in ultraviolet; it was no brighter in infrared light.

89. H. C. Urey, and A. W. Brewer. "Fluorescence in Planetary Atmospheres," Proceedings of the Royal Society of London, Vol. A241, p. 37 (1957).
It is pointed out that ions and free radicals will exist in the high atmospheres of the planets and that these ions will absorb and fluoresce in the visible and near-ultraviolet radiations. With regard to the color of Venus, it is suggested that the yellow color may be due either to colored carbon compounds in the clouds or to ionized molecules, in particular CO⁺ and CO₂⁺, or to both effects. It is suggested that the clouds cannot be composed of dust but may be composed of water.

90. Kuiper, G. P. "The Atmosphere and the Cloud Layer of Venus." The Threshold of Space, edited by M. Zelikoff. London, Pergamon Press, 1957.
A summary of some of the quantitative measurements that have been made on Venus' atmosphere is given including spectroscopic, radiometric, polarimetric, and photometric measurements. From the spectroscopic identification of CO₂ and the stability of the Venus polarization curve, is suggested that the Venus cloud layer may be composed of C₃O₂ particles. It is also reported

* Translated from Astronomical Journal (USSR), Vol. 35, p. 739 (1958).

that the near-infrared polarization curve of Venus differs markedly from the theoretically predicted curve for liquid water droplets.

91. F. Horner, "Radio Noise from Planets," Nature, Vol. 180, p. 1253 (1957).
It has been suggested that the high-frequency radio noise reportedly received from Jupiter and Venus might originate in electrical discharges, analogous to terrestrial lightning, in their atmospheres. A comparison of the observed noise intensities with the high-frequency radiation from terrestrial lightning, with proper corrections being made, shows that the observed intensities are too large by a factor of 10^6 to have arisen from a single lightning flash.
92. E. J. Öpik, "The Surface Conditions on Venus," Irish Astronomical Journal, Vol. 4, p. 37 (1956).
Since Kozyrev's measurements show that the Venus clouds are slightly yellow and absorb strongly in the near-ultraviolet region, this may indicate that the Venus clouds are not composed of water, inasmuch as terrestrial clouds are white or blue-white.
93. A. Dollfus, "Etude visuelle et photographique de l'atmosphère de Venus," L'Astronomie, Vol. 68, p. 413 (1956).
The apparent constancy in position of dark markings on Venus may imply that the period of rotation of Venus is 225 days, equal to the period of revolution.
94. J. W. Chamberlain and G. P. Kuiper, "Rotational Temperature and Phase Variation of the Carbon Dioxide Bands of Venus," Astrophysical Journal, Vol. 124, p. 399 (1956).
A CO_2 rotational temperature of $285 \pm 9^\circ\text{K}$ is derived. A series of low-dispersion spectra shows a marked change in the strength of CO_2 versus phase angle.
95. R. S. Richardson, "Observations of Venus Made at Mount Wilson in the Winter of 1954-55," Publications of the Astronomical Society of the Pacific, Vol. 67, p. 304 (1955).
A series of photographs of Venus in ultraviolet light was made, with particular interest in observing any markings on the disk. Markings of a banded type were always present on the disk, showing an intensity range of 25%.

96. D. H. Menzel and F. L. Whipple. "The Case for H_2O Clouds on Venus," Publications of the Astronomical Society of the Pacific, Vol. 67, p. 161 (1955).
The arguments for and against H_2O clouds on Venus are discussed. Lyot's polarization measurements and requirements on particle size support the H_2O hypothesis and argue against dust clouds. The objection to the H_2O hypothesis on the basis of the yellowish color of Venus, in view of white (or bluish) terrestrial clouds, is deemed questionable.
97. G. P. Kuiper, "Determination of the Pole of Rotation of Venus," Astrophysical Journal, Vol. 120, p. 603 (1954).
As the result of a series of photographs of Venus taken in infrared, red, and violet light, which showed markings consisting of several parallel bands, an identification of the pole of rotation of Venus is suggested.
98. M. A. Kozyrev, "The Emission Spectrum of the Night Sky of Venus," Publications of the Crimean Astrophysical Observatory, Vol. 12, pp. 169 and 177 (1954).
A spectrogram taken with the 50-inch astrograph disclosed a great number of molecular bands. Fifty features are listed, of which 22 are tentatively identified as being produced by N_2 and N_2^+ .
99. G. P. Kuiper, "Planetary Atmospheres and Their Origin," Atmospheres of the Earth and Planets, edited by G. P. Kuiper. Chicago, Chicago University Press, 1952. p. 306.
Observational data and theoretical suggestions are presented, with particular interest in its bearing on the origin and evolution of planetary atmospheres. Infrared spectra of Venus showing CO_2 absorption bands are reproduced. The main conclusions are that the intensity of the band varies systematically with phase angle, that day-to-day fluctuations in intensity of considerable magnitude occur, and that the observed distribution of CO_2 is often remarkably patchy over the disk.
100. J. Dunham, "Spectroscopic Observations of the Planets at Mount Wilson," Atmospheres of the Earth and Planets, edited by G. P. Kuiper, Chicago, Chicago University Press, 1952. p. 288.

The original detection and identification, in 1932, of carbon dioxide bands near 8000 Å in the spectrum of Venus is described. A temperature of about $300 \pm 50^\circ\text{K}$ was obtained from an analysis of the lines. Neither water-vapor lines near 8000 Å nor the B band of oxygen was observed. These plates were later studied extensively by Spinrad (1962) resulting in a redefinition of the Venus atmosphere.

101. H. Spinrad, "The Anomalous Inclination of the Jovian Ammonia Lines," Jet Propulsion Laboratory. To be published in the Astrophysics Journal, late 1962.

A careful measurement of the ammonia absorption lines from plates from Mt. Wilson, and Palomar (by Dunham in 1934 and Munch in 1961) show that the ammonia rotates far more slowly than the other layers of Jupiter's atmosphere. The differential rotation was measured to be about 6 km/sec.

102. L. M. Trafton, "The Jovian Environment," Jet Propulsion Laboratory, Technical Memorandum No. 33-77, 8 March, 1962.

The quantitative knowledge in existence concerning the Jovian environment and atmosphere is summarized. Topics covered include composition and structure of the atmosphere, photometric properties of the atmosphere, period of rotation, magnetic field, and the Jovian radiofrequency spectrum. References covering the most recent works in the study of Jupiter are listed. Because of the scarcity of information available on Jupiter, many of these references are listed below for completeness:

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Carr, T. D., Smith, A. G., Pepple, R., and Barrow, C. H., "18-Megacycle Observations of Jupiter in 1957," Astrophysical Journal, Vol. 127, pp. 274-83, 1961.

Carr, T. D., Smith, A. G., Bollhagen, H., Six, N. F., Jr., and Chatterton, N. E., "Recent Decameter-Wave-Length Observations of Jupiter, Saturn and Venus," Astrophysical Journal, Vol. 134, pp. 105-25, 1961.

Wildt, R., "Über die Stellardissoziation des Wasserstoffmoleküls," Zeitschrift für Astrophysik, Vol. 9, pp. 176-184, 1934.

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- Gallet, R. M., "Radio Observation of Jupiter II," Solar System, Vol. 3, ed. by G. P. Kuiper and B. M. Middlehurst. Chapter 14, pp. 500-33, University of Chicago Press, Chicago, 1961.
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Field, G. B., "Source of Radiation From Jupiter at Decimeter Wavelengths: 2 Cyclotron Radiation by Trapped Electrons," Journal of Geophysical Research, Vol. 65, pp. 1661-71, 1960.

103. F. R. Zabriskie, "Hydrogen Content of Jupiter's Atmosphere," Astronomical Journal, Vol. 67, No. 3, April 1962.

Hydrogen was definitely established by spectroscopic evidence through the work of Kiess and associates. Zabriskie has provided further analysis giving the abundance of hydrogen present.

104. Harlan Smith and James N. Douglas, "Fine Structure in Jovian Decametric Radio Noise," Yale University Observatory, Astronomical Journal, Abstr. March 1962.

This paper presents discussions of recent observations. The records show (1) there exists a radically new form of ionospheric scintillation, (2) it reflects irregularities in interplanetary plasma, and (3) much fine structure exists in the signals as they leave Jupiter.

105. G. B. Field, "Can the Jupiter Emission be Cyclotron Radiation?" Astronomical Journal, September 1961.

Recent observations of the polarization, spectrum, angular extent, and time variation of the Jovian decimeter emission are compared with a theoretical model based on cyclotron radiation by non-relativistic electrons trapped in a dipole field. Field concludes that this simple model based on cyclotron emission is inconsistent with observation and shows that synchrotron radiation by relativistic electrons provides a better model.

106. R. Hide, "Origin of Jupiter's Great Red Spot" Nature (Great Britain) Vol. 190, June 3, 1961.

A turbulent hydrodynamic model is proposed to account for the Jovian Red Spot. The spot is proposed to be a shallow "topographical feature" in the solid surface, which together with the rapid rotation of the planet, creates a turbulent regime responsible for the radio-noise bursts from this area.

107. C. H. Mayer, "The Temperature of the Planets," Scientific American, May 1961. With regard to Jupiter, photographs of radio telescope are presented and intensity data, with and without masers, and presented. The various ultra-high temperatures measured at different wavelength are discussed, and theoretical analysis regarding these extreme temperatures is briefly described.

108. J. Bolton, "Van Allen Belt Radiation on the Planet Jupiter," Electrical Engineering, Vol. 79, No. 620, July 1960.

From radio data, the existence of a magnetic field was established 200,000 miles above the surface of the planet, 85,000 miles in diameter, with an axis almost parallel to the planet's axis of rotation (as in the earth's magnetic field). The measured radiation intensity was a trillion times more than that of the earth's.

109. C. C. Kiess, C. H. Corliss, and H. K. Kiess, "High Dispersion Spectra of Jupiter," Astrophysical Journal, Vol. 132, No. 221 (1960).

The atmosphere of Jupiter has 5 km atm H_2 above the cloud level. The temperature of this level is about $170^\circ K$ or higher, perhaps as much as $200^\circ K$. These data are derived from the quadruple lines of H_2 found in the spectrum.

110. O. Struve, B. Lynds, and H. Pillans, Elementary Astronomy, Oxford University Press, 1959.

This excellent book is well illustrated and contain appreciable data in easy reference form. The planet Jupiter is discussed only briefly while

the Jupiter satellites receive considerable attention including a listing of physical and orbital data, orbit sketches, and relative configuration alignment representations.

111. A. Borgess, and L. Dunkelmann, "Ultraviolet Reflectivities of Mars and Jupiter," Astrophysical Journal, Vol. 129, p. 236 (1959).
Ultraviolet observations were made from an Aerobee rocket 140 km above the White Sand Proving Ground. A reflectivity of 0.26 at 2700 A was measured for Jupiter.
112. G. P. Kuiper, "The Atmospheres of the Earth and the Planets," University of Chicago Press, 1952.
With regard to Jupiter (as for the other planets) orbital and physical property data are presented including information on the atmosphere, circulation, clouds, dimensions, temperature, and satellites.
113. G. Fielder, "Structure of the Moon's Surface," Pergamon Press, N.Y., (1961).
114. Z. Kopal, "The Moon, Our Nearest Celestial Neighbor," Academic Press, Inc., New York (1960).
115. Phyllis Buwalda, "The Lunar Environment," Jet Propulsion Laboratory Technical Release No. 34-159, October 28, 1960.
116. B. Elsmore, "Radio Observations of the Lunar Atmosphere," Phil. Mag., Ser. 8, Vol. 2, 1040(1957).
117. C. H. Costain, B. Elsmore, and G. R. Whitfield, "Radio Observations of a Lunar Occultation of the Crab Nebula," M.N.R.A.S., Vol. 116, 380-385 (1956).
118. A Dollfus, "Recherche d'une Atmosphere Autour de la Lune," Ann. d'Astrophys, Vol. 19, 71-82, (1956).
119. B. Elsmore and G. R. Whitfield, "Lunar Occultation of a Radio Star and the Derivation of an Upper Limit for the Density of the Lunar Atmosphere," Nat., Vol. 176, 457-458 (1955).
120. G. F. Shilling, "A Note on the Atmosphere of Mars," J. Geophysical Research, March 1962.
A concise summary of the extreme atmospheric calculations prepared previously (item 12 below) together with a listing of pertinent Martian physical properties and newer interpretation.

121. F. J. White, (editor), Flight Performance Handbook for Powered Flight Operations, prepared by Space Technology Laboratories for JPL, March 1962. With reference to Mars, Chapter 7, "Planetary Entry," suggests three extreme exponential atmospheres for use in entry-trajectory and aerodynamic heating calculations. These atmospheres were based on data furnished JPL. The concept of exponential atmospheres has been argued against by Kopal (Ref. 23) and others. This book is, however, primarily for flight calculations and therefore does not consider in detail the Martian environments.
122. C. Sagan, Is the Martian Blue Haze Produced by Solar Protons?, Rand Corporation RM-2832-JPL, November 1961. If the Blue Haze were produced by solar protons, proton energies in excess of 2 Mev, fluxes of $10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$, and interplanetary field strengths of 10^{-8} gauss would be required. Sagan shows these values not not probable and suggests rejecting the solar proton hypothesis.
123. Carl Sagan and W. W. Kellogg, The Atmospheres of Mars and Venus, National Academy of Sciences, Washington, D.C., Publication 944, 1961. An unusually well-written technical discussion presenting a good summary of recent work, including certain unpublished information. No doubt one of the most comprehensive studies available.
124. L. Hobbs, An Annotated Bibliography of Articles on the Atmospheres of Mars and Venus, General Electric Co., R61SD175, November 1961. With reference to Mars, this report covers work prior to and during 1960. The recent extensive work at Rand and Ohio State is not covered. It is, however, an excellent and complete bibliography going back to early 1924 work, with many interesting comments by the author. The abstracts are comprehensive and well written; certain of these were incorporated in this work.
125. D. L. Lamar, "The Optical Ellipticity and Internal Structure of Mars," Rand Corporation Memorandum RM-2900-JPL, September 1961. The ellipticity measurements of Mars are examined. After considerable mathematical analysis, it is concluded that Mars may have a core similar to that of the earth.

126. G. F. Shilling, "On the Consequences of a Possible Ozonosphere on Mars," Rand P-2387, 28 July, 1961.

The presence of ozone at high altitudes on Mars is shown to be reasonable on the basis of current knowledge. Further, the existence of the ozonosphere with the higher temperatures helps to explain a number of meteorological features which are not yet fully understood.

127. J. H. Shaw and N. T. Bobrovnikoff, Preliminary Investigation of Interplanetary, Lunar and Near Planet Environments and Methods of Simulation, Ohio State University, ASD Technical Report 61-267, July 1961.

This report contains a summary of the individual studies carried out at Ohio State including a condensation of the Mars work (Ref. 28 below). Despite the rather recent publication date, the Mars references are all pre-1958 and do not include the Rand studies. The information presented here is, however, concise and represents generally accepted values for physical and orbital data. No model atmospheres are proposed.

128. G. F. Shilling, "Parametric Comparison of Model Atmospheres of Earth and Mars," Rand, RM-2817-JPL, 30 June, 1961.

The various extreme model atmospheres are compared with the ARDC 1959 earth atmosphere. The predicted Martian atmosphere has such a wide range of predicted densities for the various models that at least for altitudes above 20 km, the range of predicted Martian densities includes the earth values. A discussion of probable Mars surface meteorology and favorable comparison with the conditions in the Chang Tan desert in Tibet is included.

129. B. Haurwitz, "Effect of Errors in Surface Temperature and Temperature Lapse Rate on the Vertical Distribution of Pressure and Density in the Mars Atmosphere." RM-2817-JPL, Rand Corporation, 30 June, 1961.

The surface pressure is shown to be the most important parameter to determine accurately. Error calculations for the atmosphere are carried out systematically assuming errors in surface, pressure, temperature, and lapse rate.

130. M. H. Davis, "Estimates of the Specific Heats of the Martian Atmosphere," RM-2817-JPL, Rand Corporation, 30 June, 1961.

The specific heats are calculated using classical kinetic theory assuming an atmosphere of N_2 (87-99%), CO_2 (0-17%), and A (0-6%). The values of C_p vary from 0.94 to -0.038 joules/g $^{\circ}C$ for volume concentrations of CO_2 from 0-10% and argon concentration from 0-10%.

131. G. F. Shilling, "Extreme Model Atmospheres of Mars," RM-2782-JPL, Rand Corporation, 22 June, 1961.

An extensive analysis of three proposed model atmospheres: (1) assuming convective equilibrium throughout, (2) convective equilibrium to assumed tropopause and conductive equilibrium above, and (3) a conjectural model assuming an appreciable amount of ozone exists in the upper atmosphere. The resulting density, temperature, and pressure gradients are calculated and discussed.

132. M. H. Davis, "Properties of the Martian Atmosphere," RM-2817-JPL, Rand Corporation, May 1961.

Suggested means, as well as extreme values, are presented for the total atmospheric mass, surface acceleration of gravity, surface pressures, mean surface temperature, atmospheric composition, mean molecular weight, dry adiabatic lapse rate, and temperature of the stratosphere (above the tropopause).

133. G. F. Shilling, "Preliminary Remarks on a Permissible Model of the Lower Atmosphere of Mars," RM-2769-JPL, Rand Corporation, April 1961.

A discussion of the general features of a probable Martian atmosphere pointing out that the Martian atmosphere could resemble the earth's atmosphere on a high plateau. At this time, Shilling felt that the existence of ozone was improbable in significant quantities, a thesis which he later revised (see Ref. 1 above).

134. D. S. Kirby, "The Surface Gravity of Mars," (incl. in) RM-2769-JPL, Rand Corporation, 28 April, 1961.

The surface gravity is computed considering uncertainties in planet mass, radius, oblateness, and rotation. The values of the relative surface gravity, based on earth units, vary between 0.368 and 0.509 for the most extreme cases.

135. D. Deirmendjian, "Note on the Surface Pressure Estimates of the Martian Atmosphere," (incl. in) RM-2769-JPL, Rand Corporation, 28 April, 1961.
The viewpoint is given that the methods of De Vaucouleurs (1960), Dollfus (1957), and Öpik (1960) are not very reliable in predicting surface pressures (i.e., the values of 220, 230, and 300 g/cm² respectively). It is suggested that since all the quoted methods may be affected by the same systematic errors, their consistency does not imply accuracy of the final result. It is suggested that value of 250 $\pm$ 100 g/cm² is a reasonable estimate which reflects the uncertainty existing at this time.
136. Y. Mintz, "A Note on the Temperature of the Equatorial Troposphere of Mars," (incl. in) RM-2769-JPL, Rand Corporation, 28 April, 1961.
A careful analysis is made of the Sinto and Strong (1960) radiometric data, with considerable effort to correct for the Mars surface emissivity. After the measured temperatures are reduced, an empirical troposphere temperature model is calculated using the calculated adiabatic temperature lapse rate for the equatorial troposphere and "anchoring" this to the temperature curve near surface at the time of the temperature maximum (as suggested by Hess, 1961). This model indirectly predicts a very low upper limit for the amount of water vapor present.
137. Carl Sagan, "The Abundance of Water Vapor on Mars," Astronomical Journal, March 1961.
The upper limit for water vapor abundance on Mars is 3.5×10^{-2} g/cm⁻². This value is shown to be consistent with spectroscopic tolerance, the assumed greenhouse effect temperatures and the fluctuation of the polar caps.
138. W. M. Sinton and J. Strong, "Radiometric Observations of Mars," Astrophysical Journal, Vol. 131, p. 459 (1960).
Radiometric temperature measurements of Mars were made in the 8-13 μ range. The temperature of Mars at the center of the disk was found to be 288°K. The temperature of a yellow cloud was 248°K. Dark areas were a few degrees warmer than adjacent bright regions.

139. E. J. Öpik, "The Atmosphere and Haze of Mars," Journal of Geophysical Research, Vol. 65, No. 10, p. 3057 (1960).

The blue haze is an absorbing smoke, grey and dark as soot in reflection, red in transmission. Its explanation by pure scattering is untenable. The limb darkening of Mars is mainly the result of absorption by the smoke. The opacity of the Martian atmosphere increases from the red toward the violet. In all wavelengths, the extension by the Martian atmosphere is greater than that of the terrestrial. Only about 30% of the Martian extinction is due to scattering. The atmospheric pressure, based on Dollfus' polarization estimate corrected for self-absorption, is 87 mm Hg. The photochemical breakup of CO₂ and the escape of O must lead to considerable concentrations of CO in the Martian atmosphere. (Taken from Physics Abstracts, Vol. 24, No. 768, December 1961).

140. D. S. Kirby, Summary of Orbital and Physical Data for the Planet Mars, Research Memorandum RM-2567, Rand Corporation, 1960.

An unusually complete discussion and set of tabulated values of physical constants and uncertainties in these constants is presented. Starting with the two observable quantities, mass and radius, the author derives other related physical quantities. To these are added photometric, spectroscopic, and radiometric data, and a discussion of orbital elements. The excellent bibliography contains 121 referenced works.

141. Zdenek Kopal, "Aerodynamic Effects of Planetary Atmospheres," Aerospace Engineering, December 1960.

A brief survey of the principal physical and chemical characteristics of Mars and Venus atmospheres is presented. The fallacy of using an exponential atmosphere model is discussed. The possibility of a significant magnetic field on Mars is rejected although in more recent work (1962 from JPL) Kopal reconsidered this possibility.

142. G. De Vaucouleurs, "The Physical Environment on Mars," Physics and Medicine of the Atmosphere and Space, edited by O. O. Benson and H. Strughold, New York, Wiley & Sons, 1960. Also, "Remarks on Venus and Mars," The Exploration of Space, edited by R. Jastrow, The MacMillan Company, 1960.

A knowledgeable discussion together with pertinent data on the Mars environment. The first article includes an extensive bibliography covering pertinent work from 1954 through 1959, bringing up to date DeVaucouleurs' previous comprehensive bibliography (see Ref. 45).

143. H. C. Urey, "The Atmospheres of the Planets," Handbrich der Physik., Berlin, Springer-Verlag, Vol. 52, p. 363 (1959).

Total pressure, chemical composition, temperature, clouds, violet layer, structure, and evolution of the Mars atmosphere is discussed. A review of important quantitative measurements and an extensive bibliography are included.

144. R. S. Richardson and P. E. Roques, "An Example of the Blue Clearing Observed 74 Days Before Opposition," Publications of the Astronomical Society of the Pacific, Vol. 71, p. 321 (1959).

A summary of notable instances of blue clearing and the associated opposition dates for Mars is presented. A series of photographs taken in 1958 is presented. It is concluded that the alignment of the sun, earth, and Mars is not a critical factor in the production of blue clearings.

145. A. Boggess and L. Dunkelman, "Ultraviolet Reflectivities of Jupiter and Mars," Astrophysical Journal, Vol. 129, p. 236 (1959).

Ultraviolet observations of Mars and Jupiter were made from an Aerobee rocket approximately 140 km above the White Sands missile range. Very marginal data in the 2700 A range was obtained. The computed reflectivity of Mars, 0.24, is not consistent with other observations.

146. J. H. Shaw, "The Natural Environment of the Planet Mars," Ohio State Univ. AD-242-175, February 1959.

A concise summary of important physical constants of both the planet and the planetary atmosphere is presented. Although less detailed than the more recent Rand work, the values quoted are in good agreement with recent predictions.

147. N. P. Barabashov, "Basic Results of Observations of Mars* During the Favorable Opposition of 1956," Soviet Astronomy AJ, Vol. 2, p. 814*, 1958.

* Translated from Astronomical Journal (USSR), Vol. 35, p. 827, 1958.

The results of photographic and visual observations are presented as well as those of photoelectric and spectrographic observations. Conclusions are drawn on the structure of the continent, sea, and polarcap areas of Mars and on the absorbing and scattering properties of its atmosphere.

148. C. H. Mayer, J. P. McCullough, and R. M. Sloanaker, "Radiation from Mars and Jupiter at 3.15 cm Wavelength," Astrophysical Journal, Vol. 127, p. 11, 1958.

A number of observations of Mars were made at the Naval Research Laboratory at a 3.15 cm wavelength. The resulting black-body temperature was found to be $218 \pm 76^{\circ}\text{K}$.

149. G. DeVaucouleurs, "Observations of Mars in 1958," Air Force CRC TN 59-476, 15 September 1959. AD 226514.*

Visual and photoelectric observations of Mars in 1958 from the Lowell Observatory are presented. Monochromatic magnitudes and albedos are given at 3300, 3600, 4550, 5500, and 6900 Å. Main visual cloud phenomena and surface features are illustrated. Several surface changes and an outstanding moving cloud system are discussed.

150. H. C. Urey, "The Blue Haze of Mars," Astrophysical Journal, Vol. 128, p. 736 (1958).

Objections to the concept of a condensable substance as the origin of the blue haze on Mars are discussed.

151. S. L. Hess, "Blue Haze and the Vertical Structure of the Martian Atmosphere," Astrophysical Journal, Vol. 127, p. 743 (1958).

The Martian blue haze may be a condensate rather than a dust because it can clear away rapidly. CO_2 and H_2O are both present in the atmosphere, and condensation of each into the solid phase has been suggested to explain the blue haze. It is shown that CO_2 ice clouds are far too opaque to be the cause of the blue haze.

* Air Force, Cambridge Research Center. Technical Note 59-476. 15 September, 1959. ASTIA Document 226514.

152. C. C. Kiess, C. H. Corliss, H. K. Kiess, and R. L. Corliss. "High Dispersion Spectra of Mars," Astrophysical Journal, Vol. 126, p. 579 (1957).
These experiments were designed to detect H_2O and O_2 in the Martian atmosphere. The resulting spectrograms taken at both the Slope Observatory, Hawaii, and at Georgetown College Observatory gave negative results.
153. R. S. Richardson, "Preliminary Report on Observations of Mars Made at Mount Wilson in 1956," Publications of the Astronomical Society of the Pacific, Vol. 69, p. 23 (1957).
Direct photographs show a great dust storm, clouds, and some "canals." Spectrograms failed to identify the 7820 A band of CO_2 , but infrared spectra show the A band of O_2 at 7600 A as well as water vapor lines from about 7900 to 8400 A. Significant variations in the intensity of the H_2O lines over the disk, which might indicate presence of water vapor in the atmosphere over the polar caps, could not be detected.
154. H. C. Urey and A. W. Brewer, "Fluorescence in Planetary Atmospheres," Proceedings of the Royal Society of London, Vol. A241, p. 37 (1957).
It is suggested that the blue haze of Mars arises from fluorescence by CO^+ , CO_2^+ , and N_2^+ . The blue clearings which occur at opposition, may be caused by deflection of the solar corpuscular radiation, which excites the fluorescence, by the earth's magnetic field. This thesis was later rejected by Sagan (1961, Ref. 2), above.
155. V. V. Sharanov, "On the Role of True Absorption in the Martian Atmosphere," Soviet Astronomy AJ, Vol. 1, p. 547 (1957).
It is suggested that the blue-diameter-excess in photographs of Mars is a photographic effect, and that there are no definite proofs for or against the existence of a special high-altitude scattering layer in the Martian atmosphere at the present time.
156. R. M. Goody, "The Atmosphere of Mars," Journal of the British Interplanetary Society, Vol. 16, p. 69 (1957).
A summary of the important observational facts and their interpretations is first presented. A model atmosphere is suggested, which is taken to be isothermal at an equilibrium temperature of $217^{\circ}K$ throughout the statosphere.

In the suggested troposphere, the lapse rate is 3.7°K/km , the surface temperature is 270°K , and the surface pressure is 85 mb. The importance of absorption processes in the blue layer in view of its small albedo of 0.05, is emphasized, and both CO_2 and H_2O crystals are rejected as blue-layer constituents.

157. H. C. Urey, "On the Escape of Water Vapor From Mars," Publications of the Astronomical Society of the Pacific, Vol. 68, p. 220 (1956).
A discussion of the origin, evolution, and production of water and oxygen on Mars is presented.
158. G. DeVaucouleurs, "Photographic Observations in 1956 of the Blue Clearing on Mars," Publications of the Astronomical Society of the Pacific, Vol. 69, p. 530 (1957).
A short series of photographic observations of Mars near opposition in 1956 are presented. An extensive blue clearing was recorded which reached its maximum 12 days before opposition.
159. F. Gifford, "The Surface Temperature Climate of Mars," Astrophysical Journal, Vol. 123, p. 154 (1956).
The Lowell Observatory radiometric measurements of Martian surface temperatures are analyzed, and surface-temperature climatological properties of Mars are obtained. Annual and diurnal temperature variations and seasonal isotherm maps are displayed and discussed.
160. J. Grandjean, and R. M. Goody, "The Concentration of Carbon Dioxide in the Atmosphere of Mars," Astrophysical Journal, Vol. 121, p. 548 (1955).
From observations of carbon dioxide bands in the spectrum of Mars by G. P. Kuiper, the fraction by volume of CO_2 in the planet's atmosphere is determined taking into account the fine structure of the band and the shape of the rotation lines. If the ground-level pressure of Mars is 100 mb, the fraction by volume of CO_2 is 50 times greater than in the earth's atmosphere.
161. E. P. Martz, "Variation in Atmospheric Transparency of Mars in 1939," Publications of the Astronomical Society of the Pacific, Vol. 66, p. 45 (1954).
Discussion and photographs of the blue clearing on Mars near opposition in 1939 are presented. Short-time-scale variations in transparency are emphasized. A review of suggestions as to the nature of the blue haze is included.
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162. E. C. Slipher and A. G. Wilson, "On Blue Clearings of Mars," Astronomical Society of the Pacific, Leaflet No. 301, p. 7 (1954).
A study of available photographic records shows that the time of a blue clearing is always within a few days of opposition although the blue clearing does not occur at every opposition. Whenever Mars lies very far above or below the ecliptic at opposition, the blue clearing is not observed. This suggests that perhaps the earth is somehow affecting solar radiations received on Mars and that the blue layer on Mars is associated with solar radiation.
163. G. De Vaucouleurs, Physics of the Planet Mars, London, Faber and Faber, 1954.
This paper was one of the first complete collective descriptions of the atmosphere of Mars. Important contributions up through 1953 are summarized. A bibliography of 115 references is included.
164. E. P. Martz, "Heterochromatic Photography and Photometry of Mars in 1937 and 1939," Astronomical Journal, Vol. 58, p. 221 (1953).
An analysis of an extensive series of photographs of Mars secured during the close approaches of 1937 and 1939 is presented. A number of conclusions are reached, most of them confirming previous results obtained by others. A maximum of approximately 5% excess of blue-violet diameter over red diameter is reported.
165. G. P. Kuiper, "Planetary Atmospheres and Their Origin," The Atmospheres of the Earth and Planets, edited by G. P. Kuiper. Chicago, Chicago University Press, 1952, p. 306.
A comprehensive review of observational data and theoretical suggestion are presented, with particular interest in their bearing on the origin and evolution of planetary atmospheres. Extensive consideration is given to the atmosphere of Mars.
166. A. Dollfus, "La Lumiere de la planete Mars," Comptes Rendus de l'Academie des Sciences, Vol. 235, p. 1479 (1952).

Visual measurements of the diameter of Mars are reported. The measured polar diameter, reduced at unit distance, was $9''25 \pm 0''03$ in yellow light and $9''40$ in blue light. On this basis, the altitude of the violet clouds was calculated to be about 120 km.

167. J. Dunham, "Spectroscopic Observations of the Planets at Mount Wilson," The Atmospheres of the Earth and Planets, edited by G. P. Kuiper. Chicago, Chicago University Press, 1952, p. 288.
- A detailed discussion of the abundances of oxygen and water vapor in the atmosphere of Mars is given. The final conclusion is that the upper limit for the ratio of both oxygen and water vapor in the Mars atmosphere to that in the terrestrial atmosphere is 0.0015.
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TABLE 1

THE PLANETS—ORBITAL DATA*

Planet	Symbol	No. of Satellites	Major Semi-axis (A.U.) [a]	Eccentricity [e]	Perihelion (A.U.) [R _P]	Aphelion (A.U.) [R _A]	Mean longitude			Inclination		Sidereal Mean Daily Motion (Sec) [μ]	Mean Orbital Velocity (⊕=1) V _c	Period of Revolution		
							Of Ascending Node [Ω]	Of Perihelion [ω]	Of Planet at Epoch Jan. 1, 1963 [L]	Orbital to Ecliptic [i]	Equatorial to Orbit [ε]			In Earth Years	y	d h
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Mercury	☿		0.387099	0.2056259	0.307501	0.466697	47 43 17.6	76 47 11.1	17.7	7 0 14.2	—	14,732.420	1.607271	-0.2411	0	88
Venus	♀		0.723332	0.0067935	0.718418	0.728246	76 17 33.7	130 57 57.9	128.3	3 23 39.1	—	5767.670	1.175794	0.6156	0	224 17
Earth	⊕	1	1.000000	0.0167272	0.983273	1.016727	—	102 12 3.2	99.9	—	23 26 59	3548.193	1.0	1.0	1	0 0
Mars	♂	2	1.523691	0.0933654	1.381431	1.665951	49 13 33.2	335 16 2.9	113.0	1 50 50.8	25 12	1886.519	0.8068546	1.8822	1	322 0
Jupiter	♃	12	5.202803	0.0484305	4.950829	5.454777	100 50.7	13 37 47.5	350.7	1 18 19.9	3 6.9	299.128	0.4384109	11.86	11	313 21
Saturn	♄	9	9.538843	0.0556922	9.007604	10.070082	113 15 52.6	92 12 20.4	317.0	2 29 42.2	26 44.7	120.455	0.3237816	29.46	29	167 22
Uranus	♅	5	19.181973	0.0472012	18.276561	20.087385	73 43 51.4	169 57 44	154.0	0 46 22.9	97 59	42.235	0.2283249	84.0	84	0 0
Neptune	♆	3	30.057707	0.0085724	29.800040	30.315374	131 13 24.2	44 14 51.9	223.4	1 46 26.5	29	21.532	0.1823988	164.8	164	292 0
Pluto	♇		39.51774	0.2486438	29.691899	49.343581	109 33 0.2	223 10 30.2	146.2	17 8 38.4	—	14.283	0.7590757	247.7	247	255 12

Cols. 4, 5, 8, 9, 11 and 13 The American Ephemeris and Nautical Almanac, 1957. The mean distance is equal to the major axis of the planet's orbit.

Cols. 6 and 7 computed from 4 and 5 in "Principles of Guided Missile Design" by K. Ehricke.

Col. 12 Russell, Dugan and Stewart, Astronomy, Vol. 1 (1945).

Col. 10, R. Nadile, Space General Corp.

Col. 14, V_c for ⊕ = 29.77 km/sec.

Col. 4, A.U. = 149.4 × 10⁶ km.

* From Ehrike's Space Flight copyright 1960, D. Van Nostrand Company, Inc., Princeton, N. J.

*
THE PLANETS - PHYSICAL DATA

Planet	Radius (Equator)		Ob- late- ness [ϵ]	Density		Volume $\oplus = 1$	Mass		Mass Gravitational Acceleration at 45° Latitude			Mean Surface Gravity $\oplus = 1$	Escape Velocity km sec	Activity Sphere (A.U.)	Period of Rotation, ω		
	n. mi.	km		$\oplus = 1$	Water = 1		$\frac{M_{\odot}}{M_{\text{planet}}}$	$\oplus = 1$	$g_{\oplus}$ units	cm/sec ²	ft/sec ²				h.	m.	rad/sec
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
(Sun)	375,557	696,000	—	0.2554	1.41	1.302×10^6	1.0	3.3253×10^5	—	—	—	27.89	617.0	—	244.2 (Equ.) 334.5 (75°λ)		—
Mercury	1350	2500	0	0.9058	5.00	0.06	6.12×10^4 $\pm 43,000$	0.0543	0.35238	346.3904	11.36449	0.27	3.9	0.000746	—	1.98333×10^{-4}	
Venus	3348	6200	0	0.8877	4.90	0.92	4.08645×10^5 ± 208	.8148	0.85805	843.4703	27.67285	0.85	10.3	0.00412	$230^d \pm 50^d$		7.93013×10^{-5}
Earth	3440	6378.39	$\frac{1}{297}$	1.0	5.52	1.0	3.32488×10^4	1.0	1.00000	983.008	32.25085	1.00	11.2	0.00618	23	56.068	7.31958×10^{-5}
Mars	1787	3310	$\frac{1}{192}$	0.7609	4.20	0.153	3.0880×10^4 ± 3000	0.1077	0.40894	401.9938	13.18875	0.38	5.1	0.00378	24	37.38	7.08821×10^{-5}
Jupiter	37,732	69,880	$\frac{1}{16.4}$	0.2409	1.33	1318	1.0474×10^5 ± 0.03	318.35	2.81509	2767.252	90.78892	2.64	60.2	0.3216	9	50.5	1.77341×10^{-4}
Saturn	31,075	57,550	$\frac{1}{9.5}$	0.1286	0.71	736	3.49764×10^5 ± 0.27	95.3	1.29640	1274.368	41.80986	1.17	36.3	0.3246	10	2	1.73953×10^{-4}
Uranus	13,769	25,500	$\frac{1}{14}$	0.2283	1.26	64	2.2869×10^4 ± 300	14.58	0.97479	958.2298	31.43792	0.92	22.0	0.346	10	48	1.61605×10^{-4}
Neptune	13,499	25,000	$\frac{1}{45}$	0.2917	1.61	60	1.9314×10^4 ± 300	17.26	1.14183	1122.431	36.82509	1.12	25.1	0.5805	15	48	1.10464×10^{-4}
Pluto	—	—	—	—	—	1.0(?)	4.0×10^5 $\pm 30,000$	0.8312	0.40096	394.151	12.93144	?	?	0.2366	—	—	

Cols. 3, 5 and 6, H. C. Urey, The Planets (1952), **except for Sun.**

Cols. 6 and 7, Russell, Dugan and Stewart, Astronomy I (1945)

Col. 8, W. Rabe, Astronautical Journal, Vol. 55, pp. 112-126, May 1950

Col. 15, The activity sphere describes the space in which the planet, rather than the sun should be regarded as center body in the perturbation analysis of hyperbolic encounter between the planet and a particle of negligible mass. The activity sphere, therefore, may be used to define the circumplanetary space (e.g. circumterrestrial space). Values computed by K. Ehrike, "Principles of Guided Missile Design."

* From Ehrike's Space Flight Copyright 1960, D. Van Nostrand Company Inc., Princeton, N.J.

TABLE 3

THE PLANETS—SURFACE DATA *

Planct	Circular Velocity at Equat. Radius Distance			Condi- tion of Visible Surface	Albedo	Temperature (°K)			Atmosphere	
	km/sec	ft/sec	A.U./sec			Black Spher.	Max. (Day- side)	Av. Temp.	Composition	Abund- ance N.P.T. (cm)
1	2	3	4	5	6	7	8	9	10	11
Mercury	2.94276	9.6547×10^4	1.57737×10^{-10}	S	0.058	450	625	—	Traces of A ⁴⁰ , Kr, X(?)	—
Venus	7.231538	2.37258×10^4	3.15795×10^{-10}	C	0.76- .80	329	700	700	CO, CO, N ₂ O CH ₄ , C ₂ H ₄ , C ₃ H ₈ , NH ₃ , N ₂	100,000 <100 <100 <20 <3 <1 <4 (abundant)
Earth	7.90959	2.59497×10^4	3.45381×10^{-10}	S	0.39	279	349	246	N, O, CO, CH ₄ , N ₂ O O ₃	625,000 168,000 220 1.2 0.4 0.3
Mars	3.60036	1.18122×10^4	1.57143×10^{-10}	S	0.148	225	307	217	CO, SO ₂ , O ₃ , N ₂ O CH ₄ , C ₂ H ₄ , C ₃ H ₈ , NH ₃ , [Mostly N ₂ (?) A(2200?)]	440 <0.003 <0.05 <200 <10 <2 <1 <2
Jupiter	42.5467	1.395886×10^4	1.54755×10^{-9}	C	0.51	122	145	102	CH ₄ , NH ₃ , H ₂	15,000 700 large amt.
Saturn	25.6560	8.41733×10^4	1.12049×10^{-9}	C	0.50	90	107	76	CH ₄ , NH ₃ , O ₃ , SO ₂ , H ₂	35,000 <250 <0.1 <0.01 LARGE AMT.
Uranus	15.0733	5.14215×10^4	6.58391×10^{-10}	C	0.66	64	69	49	CH ₄ , O ₃ , SO ₂	220,000 <0.1 <0.01
Neptune	16.5651	5.4347×10^4	2.2946×10^{-9}	C	0.62	51	56	40	CH ₄ , H ₂	370,000 LARGE AMT.
Pluto	7.43214	2.43836×10^4	5.0307×10^{-9}	?	0.16	45	60	42	—	—

Col. 7 : Perfect conductor.

Cols. 6, 8, 11 : G. P. Kuiper, *The Atmospheres of the Earth and the Planets* (1952) Chapter XII, Table 1 and Table 9. N.P.T. (cm): equivalent height of atmosphere component at normal pressure and temperature. The Earth's atmosphere is equivalent to about 800,000 cm (N.P.T.).

Col. 5 : S=solid, C=clouds.

* From Ehrike's *Space Flight* Copyright 1960, D. Van Nostrand Company, Inc., Princeton, N.J.

TABLE 4
THE SATELLITES OF THE SOLAR SYSTEM *

Planet	Satellite	Stellar Magnitude	App. Distance as seen from ☉ (Sec. of Arc)	Distance from Planet		Period of Revolution		Eccentricity, (e)	Inclination				Direction of Rotation	Diameter (km)	Mass		Escape Velocity		Surface g ⊕ = 1	Atmosphere Component (cm) N.P.T.
				Planet Radius = 1	km	d h m	Days		Satellite Orbit to its Proper Plane (or the Planet's Equator)	Mean inc. of Proper Plane to Planet's Orbit	Mean inc. of Satellite's Orbit to Planet's Orbit	Longitude of Ascending Node			ξ = 1	ζ = 1	km sec	ft sec		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Earth	Moon	−12.5	529.75	60.267	384,400	27 7 43.19	27.321661	0.05490	28° 35' to 18° 19'	5° 8.55'			Direct	3476	0.2259	1	2.372	7873	0.1650	SO ₂ (<0.0003) O ₂ (<0.005) Kr (?)
Mars	Phobos	11.5	8.46	2.79	9350	0 7 39.23	0.3189103	0.021	1 8	25° 11'	26° 19'		Direct	~ 15						
	Deimos	13	21.25	6.93	23,500	1 6 17.92	1.2631354	0.003	1 46	24 16	26 2		Direct	~ 8						
Jupiter	V	13	48.06	2.540	181,500	0 11 57.38	0.49817938	0.0028	27.3	3 6.9	3 34.2		Direct	75–150						
	I 10	5.5	111.78	5.905	422,000	1 18 27.56	1.76913783	0.0	1.6	3 6.7	3 8.3		Direct	3730	0.2236	0.99	2.279	7476	0.1337	CH ₄ (<200) NH ₃ (<40)
	II Europa	5.7	177.86	9.401	671,400	3 13 13.70	3.55188113	0.0003	28.1	3 5.8	3 33.9		Direct	3150	0.1446	0.64	1.994	6541	0.1286	CH ₄ (<200) NH ₃ (<40)
	III Ganymede	5.1	283.7	14.995	1,071,000	7 3 42.56	7.15455265	0.0015	11.0	3 2.3	3 13.3		Direct	5150	0.4766	2.11	2.831	9288	0.1586	CH ₄ (<200) NH ₃ (<40)
	IV Callisto	6.3	498.99	26.379	1,884,000	16 16 32.19	16.68901862	0.0075	15.2	3 42.7	3 57.9		Direct	5180	0.2982	1.32	2.233	7325	0.0981	CH ₄ (<200) NH ₃ (<40)
	VI	13.7	3037	161	11,500,000	240.7	250.7	0.155			28 45	181°	Direct	120?						
	VII	16	3113	165	11,750,000	260	260	0.207			27 58	243	Direct	50?						
	X	17.8	3116	165	11,750,000	260	260	0.08			28	82	Direct	20?						
	XI	16	5990	315	22,500,000	692	692	0.21			148 1	208	Retrograde	25?						
	VIII	17.6	6240	330	23,500,000	739	713–768	0.29–0.45			157	61	Retrograde	50?						
	IX	17.4	6360	332	23,700,000	758	758	0.1–0.4			163	232	Retrograde	22?						
	XII				21,000,000															
Saturn	Mimas	12.1	26.83	3.11	185,700	0 22 37.09	0.9424219	0.019	1 31	26 44.7	26 25.4		Direct	450?	0.000117	0.000516	0.1498	491	0.00508	
	Enceladus	11.6	34.42	3.99	238,200	1 8 53.11	1.3702178	0.0001	1.4	26 44.7	27 2.4		Direct	500?	0.000264	0.00117	0.2139	702	0.00933	
	Tethys	10.5	42.6	4.94	294,800	1 21 18.44	1.8878025	0.0	1 5.6	26 44.7	30 9.9		Direct	1100?	0.00206	0.0088	0.3956	1298	0.01450	
	Dione	10.7	54.57	6.33	337,700	2 17 41.16	2.7369159	0.002	0 0	26 44.7	26 44.7		Direct	1100?	0.00316	0.014	0.4990	1637	0.02306	
	Rhea	10	76.20	8.84	527,500	4 12 25.20	4.5175026	0.0009	20.5	26 41.9	27 50.3		Direct	1600?	0.00678	0.03?	0.6055	1987	0.02335	
	Titan	8.3	176.67	20.48	1,223,000	15 22 41.41	15.9454201	0.0289	18.3	26 7.1	26 46.1		Direct	4200	0.4337	1.92	2.990	9811	0.21694	CN ₄ (20,000) NH ₃ (<300)
	Hyperion	13	214.13	24.82	1,484,000	21 6 38.40	21.2766667	0.1043	1 31	26 44.7	28 15.7		Direct	400?	<0.000136	<6 × 10 ^{−4}	<0.1713	<562	<0.0075	
	Japetus	10.1 to 11.9	514.73	59.68	3,563,000	79 7 55.54	79.330234	0.0284	13 51.8	16 18.1	26 17 to 26 56		Direct	1300?	0.00429	0.019	0.5325	1747	0.0223	
	Phoebe	14.5	1870.4	216.8	12,950,000	550 10.6	550.4416	0.1659	(148.9)	(174.7)	175 18.7		Retrograde	300?						
Uranus	Ariel	15.2	13.78	7.35	191,800	2 12 29.35	2.5203796	0.007	(0)	—	97 59		Retrograde	500?						
	Umbriel	15.8	19.2	10.2	267,300	4 3 27.61	4.1441748	0.008	(0)	—	97 59		Retrograde	400?						
	Titania	14	31.5	16.8	438,700	8 16 56.45	8.705865	0.023	(0)	—	97 59		Retrograde	1000?						
	Oberon	14.2	42.12	22.4	586,600	13 11 7.06	13.463235	0.01	(0)	—	97 59		Retrograde	900?						
	Miranda				130,100															
Neptune	Triton	13.6	16.23	14.2	354,000	5 21 2.66	5.8768437	0.0	(160)		140 (1900)		Retrograde	4500?	0.4066	1.8	2.7972	9177	0.1772	
	Nereid				6,000,000															

Cols. 3-8, 9, 10-13, 15 and 17, Russell, Dugan and Stewart, *Astronomy I* (1945)

Col. 9, 14-20, K. Ehrike, *Principles of Guided Missile Design*

* From Ehrike's *Space Flight* Copyright 1960, D. Van Nostrand Company, Inc., Princeton, N. J.

Col. 16, Computed from $m_p/m_c = 4.427$

Col. 23, G. Kuiper, *The Atmosphere of the Earth and the Planets* (1952), P. 308; cf. Cols. 22 and 23 in Table 3-1b

Table 4

TABLE 5

THE MAJOR ASTEROIDS *

No.	Name	EPOCH t_0	Longitude		Inclination of orbital plane to ecliptic. i	Eccen- tricity e	Mean daily motion sec	Major semi-axis A.U.	Perihelion R_p A.U.	aphelion R_A A.U.	Closest Approach to Earth A.U.	Diameter Miles	Period of Rotation h m	Albedo
			PERHELION ω	ASCENDING NODE Ω										
1	Ceres	1957 June 11	71.853	80.514	10.607	0.0759	770.695	2.7675	2.5574	2.9776		480		0.06
2	Pallas	1957 June 11	309.759	172.975	34.798	0.2340	768.884	2.7718	2.1232	3.4204		304		0.07
3	Juno	1957 June 11	246.133	170.438	12.993	0.2585	814.046	2.6683	1.9785	3.3581		120		0.12
4	Vesta	1957 June 11	149.134	104.102	7.132	0.0889	977.646	2.3617	2.1517	2.5717		240		0.26
7	Iris	1949 Mar. 25	144.093	259.829	5.509	0.2315	963.378	2.3849	1.8328	2.9370			6 12	
15	Eunomia	1900 Jan.	94.98	294.42	11.76	0.1870	825.347	2.6439	2.1495	3.1383			3 2	
116	Sirona	1929 Apr. 22	91.551	64.842	3.580	0.1404	770.820	2.7672	2.3787	3.1557			9 40	
345	Tercidina	1925 Jan. 1	228.308	213.246	9.728	0.0613	1000.550	2.3255	2.1829	2.4681			8 47	
433	Eros	1931 Jan. 18	177.930	304.071	10.831	0.2398	2015.293	1.4581	1.1084	1.8078	0.1742 (1931)	15	5 16	
434	Hungaria	1925 Jan. 1	123.100	175.196	22.504	0.0737	1308.770	1.9443	1.8010	2.0876				
719	Albert	1911 Oct. 2	151.940	186.094	10.825	0.5406	853.665	2.5852	1.1876	3.9828		2-3		
887	Alinda	1942 Jan. 31	348.119	111.029	9.024	0.5398	886.351	2.5212	1.1602	3.8822				
944	Hidalgo	1948 Feb. 29	57.506	21.273	42.529	0.6557	254.384	5.7944	1.9950	9.5938		15-30		
1019	Strackea	1924 Mar. 14	121.198	144.244	26.972	0.0716	1342.468	1.9116	1.7747	2.0485				
1025	Riema	1943 Dec. 22	347.568	163.100	26.871	0.0389	1274.509	1.9790	1.9020	2.0560				
1139	Atami	1941 June 19	205.517	213.215	13.102	0.2552	1305.814	1.9472	1.4503	2.4441				
1172	Aneas	1948 Aug. 7	45.617	246.784	16.687	0.1029	300.254	5.1881	4.6542	5.7220				
1173	Anchises	1948 Aug. 7	30.710	284.132	6.980	0.1376	308.455	5.0958	4.3946	5.7970				
1208	Troilus	1948 Aug. 7	292.565	47.985	33.694	0.0924	302.757	5.1595	4.6828	5.6362				
1221	Amor	1948 June 3	25.549	171.202	11.924	0.4346	1334.746	1.9190	1.0850	2.7530	0.1075 (1932)			
1235	Schorria	1931 Dec. 8	43.005	12.767	25.020	0.1537	1343.831	1.9103	1.6167	2.2039				
1404	Ajax	1948 Aug. 7	57.197	332.320	18.132	0.1118	302.437	5.1631	4.5859	5.7403				
1437	Diomedes	1948 Aug. 7	126.771	315.330	20.563	0.0436	304.209	5.1431	4.9189	5.3673				
1509	Esclangona	1939 Jan. 1	267.061	283.286	22.320	0.0329	1391.117	1.8668	1.8054	1.9282				
1566	Icarus	1950 Aug. 7	30.912	87.746	22.979	0.8266	3171.432	1.0777	0.1869	1.9685	0.038 (1968)			
1580	Betulia	1952 Dec. 14	158.888	61.874	52.037	0.4928	1090.753	2.1954	1.1135	3.2773				
1583	Antiochus	1950 Nov. 15	186.229	221.067	28.303	0.0542	292.703	5.2770	4.9910	5.5630				
1600	1947 UC	1948 Feb. 19	49.765	60.314	21.177	0.0376	1411.228	1.8490	1.7795	1.9185				
1620	Geographos	1954 Dec. 24	276.211	336.999	13.325	0.3352	42.612	1.2441	0.8271	1.6611	0.032 (1969)	1		
	1948 Oa	1948 Oct. 7	126.314	274.191	9.397	0.4360	36.960	1.3679	0.7715	1.9643				
	Apollo	1932 Apr. 25	284.878	36.077	6.422	0.5663	1958.60	1.4861	0.6445	2.3277	0.0699 (1932)	1-2		
	Adonis	1936 Feb. 25	39.537	352.538	1.480	0.7792	1284.03	1.9692	0.4348	3.5036	0.0161 (1936)	1-2		
	Hermes	1937 Nov. 7	90.687	35.367	4.685	0.4746	2420.68	1.2904	0.6780	1.9028	0.0052 (1937)	<1		

¹Ref. Ephemerides of minor planets by the Institute of Theoretical Astronomy at Leningrad except for Geographos and 1948 Oa where elements were computed by Prof. S. Herrick, University of California; taken from K. Ehrike, *Principles of Guided Missile Design*.
* From Ehrike's *Space Flight* Copyright 1960, D. Van Nostrand Company, Inc., Princeton, N. J.

TABLE 6

SELECTED PERIODIC COMETS

<u>Family</u>	<u>Name</u>	<u>Discovery</u>	<u>Perihelion Distance A.U.</u>	<u>Aphelion Distance A.U.</u>	<u>Orbital Inclination deg</u>	<u>Period yrs</u>
JUPITER						
	Encke	1818	0.3	4.1	12.5	3.3
	Biela	1826	0.9	6.2	12.6	6.6
	Faye	1843	1.6	5.9	10.6	7.3
	Brorsen I	1846	0.6	5.6	29.4	5.5
	d'Arrest	1851	1.4	5.7	18.1	6.6
	Tempel I	1867	1.8	4.8	9.8	6.0
	Tempel II	1873	1.3	4.7	12.8	5.2
	Wolf I	1884	2.4	5.8	27.3	8.3
	Finlay	1886	1.1	6.2	3.4	6.9
	Brooks II	1889	1.9	5.4	5.6	6.9
	Holmes	1892	2.1	5.1	20.8	6.9
	Perrine I	1896	1.2	5.8	15.7	6.5
	Zinner	1900	1.0	6.0	30.7	6.6
	Borelli	1905	1.4	5.8	30.5	6.9
	Schaumasse	1911	1.2	6.8	14.7	8.0
	Neujmin II	1916	1.3	4.8	10.6	5.4
SATURN						
	Tuttle I	1858	1.0	10.3	55.0	13.5
	Neujmin I	1913	1.5	12.0	15.2	17.7
URANUS						
	Pons-Forbes	1818	0.7	18.0	28.9	28.7
NEPTUNE						
	Pons-Brooks	1812	0.8	33.7	74.0	71.6
	Olbers	1815	1.2	33.6	44.6	72.7
	Westphal	1852	1.3	30.0	40.9	61.7
	Halley	unknown	0.6	35.5	102.2	75.0

TABLE 7

MODEL VENUSIAN ATMOSPHERE

Height km	Pressure atm	Temperature °K	Density gm/cc
0	10	700	5.09×10^{-3}
10	6.27	651.7	3.43×10^{-3}
20	3.79	603.3	2.24×10^{-3}
30	2.20	555.0	1.41×10^{-3}
40	1.21	506.6	8.52×10^{-4}
50	6.30×10^{-1}	458.3	4.90×10^{-4}
60	3.04×10^{-1}	409.9	2.64×10^{-4}
70	1.34×10^{-1}	361.6	1.32×10^{-4}
80	5.25×10^{-2}	313.2	5.97×10^{-5}
90	1.76×10^{-2}	264.9	2.36×10^{-5}
97.21	7×10^{-3}	230	1.08×10^{-5}
100	4.81×10^{-3}	228.5	7.50×10^{-6}
110	1.23×10^{-3}	222.9	1.97×10^{-6}
120	3.04×10^{-4}	217.4	4.98×10^{-7}
130	7.23×10^{-5}	211.8	1.22×10^{-7}
140	1.66×10^{-5}	206.3	2.86×10^{-8}
150	3.65×10^{-6}	200.7	6.48×10^{-9}
151.28	3×10^{-6}	200	5.34×10^{-9}
160	8.85×10^{-7}	215.4	1.40×10^{-9}
168.29	3×10^{-7}	230	4.22×10^{-10}
170	2.45×10^{-7}	236.9	3.35×10^{-10}
178.24	10^{-7}	270	1.20×10^{-10}

Note: Table refers to the standard atmosphere.

TABLE 8

SOME LUNAR CONSTANTS

Mean Diameter-----	3476km (0.273 earth's diameter)
Mass-----	0.0123 (1/81.3 earth's mass)
Mean Density-----	3.34
Surface Gravity-----	0.16 earth's gravity
Escape Velocity-----	2.4 km/sec
Mean Distance from Earth-----	3.844×10^5 km
Eccentricity of Orbit-----	0.0549
Average Inclination of Orbit to Ecliptic-----	5.1°
Orbital Velocity-----	1.03 km/sec
Period of Rotation-----	27.32 days
Albedo-----	0.07
Surface-----	41% never visible from earth

TABLE 9

PERMISSIBLE EXTREME RANGES OF MEAN VALUES OF ATMOSPHERIC
PARAMETERS NEAR THE SURFACE OF MARS

Parameter	Symbol (unit)	Earth's atmosphere	Mars Atmosphere		
			Maximum probable	Mean	Minimum probable
Mass per unit surface area	M (gm cm ⁻²)	1033	340	227	114
Mean accelera- tion of gravity	g_o (cm sec ⁻²)	980	390	375	360
Surface pressure	p_o (millibars)	1013	133	85	41
Mean molecular mass	m	28.97	30	29	28
Atmospheric temperature near surface	T_o (°K)	288	300	250	200
Atmospheric density near surface	ρ_o (g cm ⁻³)	1.225×10^{-3}	2.4×10^{-4}	1.2×10^{-4}	4.6×10^{-5}
Scale height near surface	H_o (km)	8.4	25	19.1	14
Specific heat of air at constant pressure	C_p (10^7 ergs gm ⁻¹ (°K) ⁻¹)	1.0	1.05	1.0	0.95
Adiabatic lapse rate	Γ (°K km ⁻¹)	-9.76	-4.1	-3.75	-3.4
Limit of convective atmosphere	Z_{∞} (km)	29.5	79	67	53

Table 9

TABLE 10

PERMISSIBLE RANGES OF PARAMETERS FOR MODEL 1 MARS ATMOSPHERE IN
CONVECTIVE EQUILIBRIUM THROUGHOUT

Altitude (km)	Temperature (°K)			Pressure (mb)			Density (gm cm ⁻³)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0	200.0	250.0	300.0	41.04	85.125	132.6	7.40×10^{-5}	1.19×10^{-4}	1.49×10^{-4}
2	192.4	242.5	292.6	36.0	76.5	121.4	6.75	1.10	1.40
4	184.8	235.0	285.1	31.3	68.6	110.9	6.11	1.02	1.31
6	177.3	227.5	277.7	27.1	61.3	101.0	5.52	9.39×10^{-5}	1.22
8	169.7	220.0	270.3	23.4	54.5	91.8	4.98	8.64	1.14
10	162.1	212.5	262.9	20.0	48.3	83.2	4.45	7.93	1.07
12	154.5	205.0	255.4	17.0	42.6	75.2	3.97	7.25	9.92×10^{-5}
14	146.9	197.5	248.0	14.3	37.4	67.8	3.51	6.61	9.21
16	139.4	190.0	240.6	11.9	32.7	60.9	3.08	6.00	8.52
18	131.8	182.5	233.1	9.82	28.4	54.5	2.69	5.43	7.87
20	124.2	175.0	225.7	8.02	24.5	48.6	2.33	4.89	7.25
22	116.6	167.5	218.3	64.6	21.0	43.2	2.00	4.38	6.66
24	109.1	160.0	210.9	5.13	17.9	38.3	1.70	3.91	6.12
26	101.5	152.5	203.4	4.00	15.2	33.7	1.42	3.47	5.58
28	(93.9)	145.0	196.0	3.07	12.7	29.6	1.18	3.06	5.09
30	(86.3)	137.5	188.6	2.29	10.6	25.8	9.57×10^{-6}	2.68	4.61
32	(78.7)	130.0	181.1	1.68	8.70	22.4	7.70	2.33	4.16
34	(71.2)	122.5	173.7	1.19	7.07	19.3	6.75	2.01	3.74
36	(63.6)	115.0	166.3	.806	5.67	16.6	5.19	1.72	3.36
38	(56.0)	107.5	158.9	.522	4.48	14.1	3.36	1.45	2.99
40	(48.4)	100.0	151.4	.317	3.48	11.9	2.36×10^{-6}	1.22×10^{-5}	2.65×10^{-5}
53.85	0			0			0		
66.57		0			0			0	
79.17			0			0			0

Table 10

TABLE 11

PERMISSIBLE RANGES OF PARAMETERS FOR MODEL II MARS ATMOSPHERE

(Convective equilibrium to tropopause altitude and conductive equilibrium above.)

Altitude (Km)	Temperature (°K)			Pressure (mb)			Density (gm cm ⁻³)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0	200.0	250.0	300.0	41.04	85.125	132.6	7.40×10^{-5}	1.19×10^{-4}	1.49×10^{-4}
2	192.4	242.5	292.6	36.0	76.5	121.4	6.75	1.10	1.40
4	184.6	235.0	285.1	31.3	68.6	110.9	6.11	1.02	1.31
6	177.3	227.5	277.7	27.1	61.3	101.0	5.52	9.39×10^{-5}	1.22
8	169.7	220.0	270.3	23.4	54.5	91.8	4.98	8.64	1.14
10	162.1	212.5	262.7	20.0	48.3	83.2	4.45	7.93	1.07
12	154.5	205.0		17.0	42.6	75.3	3.97	7.25	9.68×10^{-5}
14	146.9	197.5		14.3	37.4	68.1	3.51	6.61	8.76
16	139.4	190.0		11.9	32.7	61.7	3.08	6.00	7.93
18	131.8	182.5		9.82	28.4	55.8	2.69	5.43	7.18
20	124.2	175.0		8.02	24.5	50.5	2.33	4.89	6.49
22	116.6	167.5		6.46	21.0	45.7	2.00	4.38	5.88
24	109.1	160.0		5.13	17.9	41.3	1.70	3.91	5.32
26	101.5			4.00	15.2	37.4	1.42	3.32	4.81
28				3.10	12.9	33.9	1.10	2.82	4.35
30				2.40	11.0	30.6	8.51×10^{-6}	2.39	3.94
32				1.86	9.31	27.7	6.59	2.03	3.56
34				1.44	7.90	25.1	5.10	1.73	3.23
36				1.11	6.71	22.7	3.95	1.47	2.92
38				.861	5.70	20.5	3.06	1.25	2.64
40				.667	4.84	18.6	2.37	1.06	2.39
45				.352	3.22	14.5	1.25	7.03×10^{-6}	1.86
50				.185	2.14	11.3	6.58×10^{-7}	4.67	1.45
55				.0978	1.42	8.79	3.47	3.10	1.13
60				.0516	.944	6.84	1.83	2.06	8.80×10^{-6}
65				.0272	.627	5.33	9.65×10^{-8}	1.37	6.86
70				.0143	.417	4.15	5.09	9.10×10^{-7}	5.34
75				.00756	.277	3.23	2.69	6.05	4.16
80				.00399	.184	2.52	1.42×10^{-8}	4.02×10^{-7}	3.24×10^{-6}

Table 11

TABLE 12

MODEL III MARS ATMOSPHERE (CONJECTURAL)

Altitude (km)	Temperature (°K)	Pressure (mb)	Density (gm cm ⁻³)
0	250.0	85.125	1.19×10^{-4}
1	246.3	80.7	1.14
2	242.5	76.6	1.10
3	238.8	72.4	1.06
4	235.0	68.6	1.02
6	↓	61.5	9.12×10^{-5}
8	↓	55.1	8.17
10	↓	49.3	7.32
15	↓	37.5	5.56
20	↓	28.5	4.23
25	↓	21.6	3.21
30	↓	16.4	2.44
35	↓	12.5	1.86
40	235.0	9.50	1.41
50	246.0	5.63	7.98×10^{-6}
60	257.0	3.42	4.64
70	268.0	2.12	2.76
80	279.0	1.34	1.68
90	290.0	8.60×10^{-1}	1.03
100	301.0	5.62	6.51×10^{-7}
110	↓	3.74	4.33
120	↓	2.49	2.89
130	301.0	1.66	1.92
140	271.0	1.10	1.27
150	241.0	6.88×10^{-2}	9.95×10^{-8}
160	211.0	4.06	6.71
170	181.0	2.21	4.26
180	151.0	1.08	2.49
190	(121.0)	4.48×10^{-3}	1.29
200	(91.0)	1.45×10^{-3}	4.44×10^{-9}

TABLE 13

SOLAR-SPECTRAL-IRRADIANCE DATA — 0.22 TO 7.0 MICRONS

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λ^a (μ)	H_λ ($w/cm^2\mu$)	P_λ (%)	λ (μ)	H_λ ($w/cm^2\mu$)	P_λ (%)	λ (μ)	H_λ ($w/cm^2\mu$)	P_λ (%)	λ (μ)	H_λ ($w/cm^2\mu$)	P_λ (%)
0.22	0.0030	0.02	0.395	0.120	3.54	0.57	0.187	33.2	1.9	0.01274	93.02
0.225	0.0042	0.03	0.40	0.154	9.03	0.575	0.187	33.9	2.0	0.01079	93.87
0.23	0.0052	0.05	0.405	0.188	9.65	0.58	0.187	34.5	2.1	0.00917	94.58
0.235	0.0054	0.07	0.41	0.194	10.3	0.585	0.185	35.2	2.2	0.00785	95.20
0.24	0.0058	0.09	0.415	0.192	11.0	0.59	0.184	35.9	2.3	0.00676	95.71
0.245	0.0064	0.11	0.42	0.192	11.7	0.595	0.183	36.5	2.4	0.00585	96.18
0.25	0.0064	0.13	0.425	0.189	12.4	0.60	0.181	37.2	2.5	0.00509	96.57
0.255	0.010	0.16	0.43	0.178	13.0	0.61	0.177	38.4	2.6	0.00445	96.90
0.26	0.013	0.20	0.435	0.182	13.7	0.62	0.174	39.7	2.7	0.00390	97.21
0.265	0.020	0.27	0.44	0.203	14.4	0.63	0.170	40.9	2.8	0.00343	97.47
0.27	0.025	0.34	0.445	0.215	15.1	0.64	0.166	42.1	2.9	0.00303	97.72
0.275	0.022	0.43	0.45	0.220	15.9	0.65	0.162	43.3	3.0	0.00268	97.90
0.28	0.024	0.51	0.455	0.219	16.7	0.66	0.159	44.5	3.1	0.00230	98.08
0.285	0.034	0.62	0.46	0.216	17.5	0.67	0.155	45.6	3.2	0.00214	98.24
0.29	0.052	0.77	0.465	0.215	18.2	0.68	0.151	46.7	3.3	0.00191	98.39
0.295	0.063	0.98	0.47	0.217	19.0	0.69	0.148	47.8	3.4	0.00171	98.52
0.30	0.061	1.23	0.475	0.220	19.8	0.70	0.144	48.8	3.5	0.00153	98.63
0.305	0.067	1.43	0.48	0.216	20.6	0.71	0.141	49.8	3.6	0.00139	98.74
0.31	0.076	1.69	0.485	0.203	21.3	0.72	0.137	50.8	3.7	0.00125	98.83
0.315	0.082	1.97	0.49	0.199	22.0	0.73	0.134	51.8	3.8	0.00114	98.91
0.32	0.085	2.26	0.495	0.204	22.8	0.74	0.130	52.7	3.9	0.00103	98.99
0.325	0.102	2.60	0.50	0.198	23.5	0.75	0.127	53.7	4.0	0.00095	99.05
0.33	0.115	3.02	0.505	0.197	24.2	0.80	0.1127	57.9	4.1	0.00087	99.13
0.335	0.111	3.40	0.51	0.196	24.9	0.85	0.1003	61.7	4.2	0.00080	99.18
0.34	0.111	3.80	0.515	0.189	25.6	0.90	0.895	65.1	4.3	0.00073	99.23
0.345	0.117	4.21	0.52	0.187	26.3	0.95	0.0803	68.1	4.4	0.00067	99.29
0.35	0.118	4.63	0.525	0.192	26.9	1.0	0.0725	70.9	4.5	0.00061	99.33
0.355	0.116	5.04	0.53	0.195	27.6	1.1	0.0606	75.7	4.6	0.00056	99.38
0.36	0.116	5.47	0.535	0.197	28.3	1.2	0.0501	79.6	4.7	0.00051	99.41
0.365	0.129	5.89	0.54	0.198	29.0	1.3	0.0406	82.9	4.8	0.00048	99.45
0.37	0.133	6.36	0.545	0.198	29.8	1.4	0.0328	85.5	4.9	0.00044	99.48
0.375	0.132	6.84	0.55	0.195	30.5	1.5	0.0267	87.6	5.0	0.00042	99.51
0.38	0.123	7.29	0.555	0.192	31.2	1.6	0.0220	89.4	6.0	0.00021	99.74
0.385	0.115	7.72	0.56	0.190	31.8	1.7	0.0182	90.83	7.0	0.00012	99.86
0.39	0.112	8.13	0.565	0.189	32.5	1.8	0.0152	92.03			

^a λ is wavelength; H_λ is spectral irradiance; and P_λ is the percentage of the solar constant associated with wavelengths shorter than λ .

TABLE 14

CHARACTERISTICS OF EXTREME ULTRAVIOLET
RADIATION (3000 TO 1300 Å)Note: h^* data for overhead sun ($Z \sim 0^\circ$). $a \times 10^b \equiv a^b$ in Φ_0 , I_0 , data.

λ or λ_1/λ_2 , Å	$h\nu$, ev	Top of Atmosphere		h^* $\Phi(h^*) \equiv \Phi_0/e$ (approx.), km	$\sigma(M)$, Absolute Absorption Cross Section for Species M, cm^2	Remarks
		Φ_0 , $\text{ph}/\text{cm}^2\text{sec}$	I_0 , $\text{erg}/\text{cm}^2\text{sec}$			
3000/ 2800	4.3	1.5^{15}	1.0^4	30-40	$\sigma(\text{N}_2, \text{O}_2, \text{O}, \text{N})$ are negligible	Below 3000 Å: Strong absorption by ozone.
2800/ 2600	4.6	6.8^{14}	5.0^3	30-40		
2600/ 2400	5.0	2.5^{11}	2.0^3	35-45	$\sigma(\text{O}_2) = 1.2 \times 10^{-17}$	2550 Å: Spectral peak of ozone absorption. Below 2420 Å: Weak photodissociation of oxygen (O_2 - Herz- berg continuum).
2400/ 2200	5.4	1.3^{14}	1.1^3	40	$(\text{O}_2) = 5 \times 10^{-24}$ [Young, 1960]	
2400/ 2000	5.9	5.3^{13}	500			
3000/ 2000	5	2.6^{15}	1.9^4	30-45		Mainly absorbed by O_3 above 2300 Å; ab- sorbed by both O_3 and O_2 below 2300 Å.
2000/ 1900	6.4	1.3^{13}	130	30-50	$\sigma(\text{O}_2) < 6 \times 10^{-21}$	
1900/ 1800	6.7	5.6^{12}	60	75	$\sigma(\text{O}_2) \sim 10^{-18}$ $\sigma(\text{O}_2) \sim 3 \times 10^{-20}$ $\sigma(\text{O}_2) \sim 1.5 \times 10^{-22}$	O_2 bands. O_2 Herzberg conti- nuum [Young, 1960]. Below 1750 Å: Strong photodissociation of O_2 (Schumann continuum).
1800/ 1700	7.1	3.5^{12}	40	85-100	$\sigma(\text{O}_2) = 10^{-19}$ $- 8 \times 10^{-19}$	
1700/ 1600	7.5	1.6^{12}	20	~ 105	8×10^{-19} $- 4 \times 10^{-18}(\text{O}_2)$	Spectral peak of O_2 dissociation.
1600/ 1500	8.0	7^{11}	9	~ 115	4×10^{-18} $- 1.1 \times 10^{-17}(\text{O}_2)$	
1500/ 1400	8.5	2.6^{11}	3.5	~ 125	$1.5 \times 10^{-17}(\text{O}_2)$ [Watanabe, 1958] $1.8 \times 10^{-17}(\text{O}_2)$ [Ditchburn and Heddle, 1953]	
1400/ 1300	9.2	8^{10} (continuum)	1.2	95-125	1.4×10^{-17} $- 4 \times 10^{-19}(\text{O}_2)$	
1403/ 1394	8.8	5^9 (Si IV)	0.07	~ 125	$1.4 \times 10^{-17}(\text{O}_2)$	
1336/ 1334	9.3	1^{10} (C II, Si II)	0.15	~ 110	$2.2 \times 10^{-18}(\text{O}_2)$	
1309/ 1302	9.5	1^{10} (Si II, O I)	0.15	~ 95	$5 \times 10^{-19}(\text{O}_2)$	
1400/ 1300	9.5	1.1^{11} (total)	1.5	95-125	4×10^{-19} $- 1.4 \times 10^{-17}(\text{O}_2)$	
2000/ 1300	6.2/ 9.5	2.5^{13} (total)	260	50-125		Mainly absorbed by molecular oxygen; no ionization.
3000/ 1300	4.2/ 9.5	2.6^{15} (total)	1×10^4	25-125		Mainly absorbed by ozone and molecular oxygen; no ionization.

Table 14

TABLE 15
CHARACTERISTICS OF THE SOLAR SPECTRUM BELOW 1300 Å

Note: h^* data estimated for summer day 1960, near noon, temperate latitudes.							
λ or λ_1/λ_2 , Å	$h\nu$, ev	Φ 235 km, $\cos Z = 0.8$, 8/23/60, New Mexico, ph/cm ² sec	Estimated for Top of Atmosphere August 1960 Φ_0, ph/cm² sec I_0, erg/cm² sec	Estimated, $\Phi^* = \Phi_0/e$, $\cos Z = 1$, km	$\sigma_d(M)$ or $\sigma_i(M)$ Absolute Cross Sections Total Absorp- tion —, or Ionization; Species M, 10 ⁻¹⁸ cm ²	Remarks	
1300-1200 Å							
1300/1200	10.0	~5 ⁹	5 ⁹ (continuum)	0.08	70-135	0.01-40 _d (O ₂)	Notation for Φ : a^b means $a \times 10^b$ throughout tables.
1265/1259	9.9	2.5 ⁹	2.5 ⁹ (lines, Si II)	0.04	~100	Rapidly variable with λ 0.5 _d (O ₂)	
1248/1239	10.0	~1 ⁹	~1 ⁹ (lines, N V)	~0.01	~105	0.5 _d (O ₂)	
1216	10.2	2 ¹¹ (3.7 ¹¹) 210 km	2 ¹¹ (H Ly α) (3.7 ¹¹) 3.7 ¹¹	3.3 (6.0) 6.0	~75 (GRD 1/19/60 estimated max. error 20%)	0.01 _d (O ₂), 0.000 _d (N ₂), 2.4 _d (NO), 2.0 _d (NO)	H Ly α : Considered as main source of normal D-region ion- ization (quiet sun).
For spectral shape of H Ly- α line see <i>Tousey</i> [1961]				~0.1		Preferred value from many ion-chamber measurements by Friedman and collaborators, NRL, up to spring 1960 (estimated experimental error 10-20%). Lowest values from earlier NRL experiments found closer to minimum of solar cycle; low value, however, possibly attributed to instrumental error.	
				0.1-10		Extreme excursion believed to be possible; actual variation probably within a factor of 10 and quite possibly less, even under conditions of major flares [<i>Friedman</i> , 1961]; H Ly- α first detected photographically at University of Colorado [<i>Rense</i> , 1953].	
1206	10.2	4 ⁹	4 ⁹ (line, Si III)	0.07	~115	15 _d (O ₂)	
1300/1200	10.0	2.1 ¹¹	2.1 ¹¹ (all lines + continuum)	3.5	70-135 see Ly- α	0.01 _d -40 _d (O ₂) rapid variation with λ 2 _d (NO) for H Ly- α	Mostly absorbed by O ₂ ; the dominant line, H Ly- α , is be- lieved to be partly absorbed by NO, causing the normal D- region ionization.
1200-990 Å							
1200/1100	~10.8	~3 ⁹	~3 ⁹ (continuum estimated)	~0.05	70-120	0.01 _d -6 _d (O ₂)	
1176	10.6	~2 ⁹	~2 ⁹ (C III)	~0.03	~100	1.3 _d (O ₂)	
1200/1100	~10.8	~2 ⁹	~2 ⁹ (other lines)	~0.03	70-120		
1200/1100	~10.8	~7 ⁹	~7 ⁹ (all lines + continuum)	~0.10	70-120	σ_d (O ₂) rapidly variable with λ	Absorbed by O ₂ ; contribution of $\leq 5\%$ to Friedman's Ly- α de- tectors (NO chamber with LiF window).
1100/1000	~11.8	~2 ⁹	~2 ⁹ (continuum estimated)	0.03	80-120	0.05-6 _d (O ₂)	
1038/1031	11.9	3 ⁹	3 ⁹ (lines, O VI)	0.06	~100	1.0 _d (O ₂); $\sigma_i = 0$	Contribution $\leq 2\%$ NO ion chamber signals.
1026	12.0	2.2 ⁹	2.2 ⁹ (H Ly- β)	0.03	~105	1.7(O ₂), 0.9 _d (O ₂)	Below 1030 Å: photoioniza- tion of molecular oxygen H Ly- β causes much of the ionization in lower E region.
1006	12.2	7 ⁸	7 ⁸ (N III)	0.01	~105	2.0 _d (O ₂), 1.5 _d (O ₂)	
1100/1000	11.8	8 ⁹	8 ⁹ (all lines + continuum)	0.13	80-120	0.05 _d -6.0 _d (O ₂); 0 _d -1.5 _d (O ₂)	See note above; absorbed mostly by O ₂ .
1000/900	~13.0	2 ⁹	$\leq 2^9$ (continuum estimated excluding Ly continuum)	≤ 0.03	110-250?	1.5 _d -54 _d (O ₂); 1.3 _d -3.8 _d (O ₂); 0.01-300 _d (N ₂)	Sharp N ₂ -absorption bands (see σ_d (N ₂)).
993/990	12.5	3 ⁹	3 ⁹ (Si II, N III, O I)	0.006	115	1.6 _d -20 _d (O ₂); 1.4 _d -10 _d (O ₂); ~0.5 _d (N ₂)	Mostly absorbed by O ₂ .
976-800 Å							
976	12.7	4 ⁹	4 ⁹ (C III line)	0.08	~115	8.5 _d , 8.0 _d (O ₂); 3 _d (N ₂)	Significant contribution to E- region ionization.
972	12.7	3 ⁹ (?)	1 ⁹ (?) (H Ly- γ)	0.02(?)	250-300	$\leq 300_d$ (N ₂), 'effective' cross section very uncertain	H Ly- γ may contribute to up per atmosphere heating (Nicolet, private communication). This line, 'missing' in all photographic spectra until recently discovered in exposure at 220 km [<i>Purcell</i> , <i>Packer</i> , and <i>Tousey</i> , 1960]. N ₂ absorption spectrum is extremely complex. σ_d (λ) varies over many orders of magnitude and is not accurately known.
949	13.0	3.5 ⁸	3.5 ⁸ (H Ly- δ)	0.006	~130	4 _d (O ₂), 3 _d (O ₂); 0.2 _d -2.0 _d (N ₂)	
937/912	~13.7	~1 ⁹	~1 ⁹ (rest of Ly series)	~0.02	115-160	4 _d -20 _d (O ₂); 3 _d -15 _d (O ₂); 0.2 _d -10 _d (N ₂);(?)	
1000/911	~12.8	8 ⁹	8 ⁹ (all lines + continuum)	0.16	110-160 (300?)	1.5 _d -50 _d (O ₂); 1.3 _d -38 _d (O ₂); 0.01 _d -300 _d (N ₂)	Significant contribution to ionization and heating in E re- gion (some also in F ₁); also see note for H Ly- γ .
912/900	13.7	3 ⁹	3 ⁹ (H Ly continuum)	0.07	~135	4 _d -14 _d (O ₂); 3.5 _d -9.7 _d (O ₂); $< 0.1_d$ -150 _d (N ₂); 7 _d (H)	Below 911 Å: photoionization of atomic oxygen (also H) H Ly continuum: dominating cause of ionization and heating of E re- gion, contributing source of F ₁ region and highest F ₂ .
900/840	~14.1	5 ⁹	5 ⁹ (H Ly continuum)	0.11	~140	2.6 _d -3.0 _d (O)	
835/833	14.9	7 ⁸	7 ⁸ (lines, O II, III)	0.17	~140	14.5 _d (O ₂); 4.7 _d (O ₂); 10 _d (N); 3.0 _d (O); σ_d (N ₂) = ?	Below 850 Å: photoionization of atomic nitrogen.
911/800	13.6/ 15.6	9 ⁹	9 ⁹ (all lines and continua)	0.20	~135	4.5 _d -30 _d (O ₂); 3.8 _d -9 _d (O ₂); σ_d (N ₂) = ?	Ionization and heating in E and F ₁ regions; see notes above.
800-500 Å							
790/888	15.7	5 ⁸	7 ⁸ (lines, O II, III)	0.018	~185	30 _d (O ₂); 13 _d (O ₂); 8 _d (N ₂); 3 _d (O); 10 _d (N)	Below 797 Å: photoionization of molecular nitrogen; σ_d (N) = σ_i (N) and σ_d (O) = σ_i (O) (val- ues taken close to those calcu- lated by Dalgarno, private communication).
780/770	16.0	4.5 ⁸	6 ⁸ (lines, Ne VIII)	0.015	~175	10 _d (N ₂); 22 _d , 11 _d (O ₂); 10 _d (N); 3.4 _d (O)	
704/702	17.6	2.8 ⁸	6 ⁸ (lines, O II)	0.016	~220	20 _d (N ₂); 25 _d (O ₂); 10 _d (N); 7 _d (N)	
800/700	17.6/ 20.7	1.2 ⁹	1.4 ⁸ -3 ⁹ (all lines + continuum)	0.04-0.10	~180 mostly	See above.	Apparently modest contribu- tion to ionization and heating of F ₁ and F ₂ region.
630/625	20.0	9 ⁸	2 ⁹ (lines, O V, Mg X)	0.064	~250	20 _d (N ₂); 23 _d (O ₂); 11 _d (N); 12 _d (O)	
610	20.3	6 ⁸	1.5 ⁹ (line, Mg X)	0.05	~250	22 _d (N ₂); 25 _d (O ₂); 10 _d (N); 12 _d (O)	
584	21.2	8 ⁸	3 ⁹ (He I res. line)	0.10	~250	22 _d (N ₂); 25 _d (O ₂); 12 _d (N); 13 _d (O)	Probably strongest monochro- matic flux dissipated in F ₂ region.
555/521/ 500	22.5/ 23.7/ 24.7	5 ⁸	1.3 ⁸ (lines, O II, IV; Si XII, C III)	0.05	~250		
700/500	17.6/ 24.7	2.8 ⁸	7.8 ⁸ (all lines + continuum)	0.26	~250	12 _d (O), 22 _d (N ₂), 11 _d (N), 12 _d (O ₂)	Dominant cause of ionization and heating in F ₂ region.
500-260 Å							
500/400	24.8/ 29.5	7 ⁸	1.5 ⁹ (all lines + continuum)	0.07	220	12 _d (O), 15 _d (N ₂), 5 _d (N); 20 _d (O ₂)	Apparently modest contribu- tion to F-region ionization and heating. Φ_0 (500/300 Å) data un- certain by a factor of about 2.
370	33.5	3 ⁸	4.5 ⁸ (line, C III)	0.024	190	10 _d (O), 13 _d (N ₂), 20 _d (O ₂), 2.6 _d (N)	
360	34.5	3 ⁸	4.5 ⁸ (C III, N III, Ne II)	0.025	190	10 _d (O), 12 _d (N ₂), 20 _d (O ₂), 5.7 _d (N)	(Identification of specific solar emission lines as shown is tenta- tive except for He ⁺ Ly- α .)
335	37.0	4.3 ⁸	8 ⁸ (line, N IV?)	0.047	190	8.5 _d (O), 10 _d (N ₂), 17 _d (O ₂), 4.3 _d (N)	
323/310	39.5	2 ⁸	4 ⁸	0.026	180	7.8 _d (O), 6 _d (N ₂), 15 _d (O ₂), 3.5 _d (N)	
304	41.0	2.1 ⁸	4 ⁹ (He ⁺ Ly- α)	0.25	180	10 _d (O), 4 _d (N ₂), 20 _d (O ₂), 2.9 _d (N)	First detected photographi- cally in 1958 [<i>Violet</i> and <i>Rense</i> , 1959] and photoelectrically in 1959 [<i>Hinteregger</i> , 1960a, b].
285/282	43.5	5 ⁸	8 ⁸ (lines, N IV, Ne III?)	0.05	160	8.5 _d (O), 5 _d (N ₂), 17 _d (O ₂), 2.3 _d (N)	
280/260	45.0/ 47.5	5 ⁸	7.5 ⁸ (lines, O II, III, IV; N V; C IV)	0.045	155	7.5 _d -8.0 _d (O); 6 _d -7 _d (N ₂); 15 _d -16 _d (O ₂); 1.9 _d -2.2 _d (N)	
400/260		4.3 ⁹	7.7 ⁹ (all lines + continuum estimated)	0.467			Major source of heating and ionization in F ₁ region.
260-60 Å							
259/228	47.5/ 54.5		1.5 ⁹ (lines, including He II Ly- β + continuum)	0.12	~150	5 _d (N ₂); 15 _d (O ₂); 7.5 _d (O)	Estimated error of a factor of 3.
228/166	54.5/ 74.0		5 ⁹ (lines + continuum)	0.5	~140	1 _d -5 _d (N ₂); 5 _d -10 _d (O ₂)	Same source of data; esti- mated error of a factor of 4.
260/166	47.5/ 74.0		~6.5 ⁹ (lines + continuum)	0.65	140-150	(Probably more than one ion-electron pair per ab- sorbed photon)	Important source of E- and F ₁ -region ionization; may be in error by as much as a factor of 4 (listed values are more likely to be too high than too low).
166/105	74/ 120		~5 ⁹ ?	~0.07?	~135	0.3 _d -1 _d (N ₂); 2 _d -5 _d (O ₂)	Least accurate estimate from 1/29/60 GRD experiment (fac- tor of 10).
105/60	100/ 205		~1.5 ⁹	~0.35	~110	Probably up to about 6 ion pairs per absorbed photon	Important source of E-region ionization; error in Φ_0 (from GRD data) estimated as high as factor of 5.

Note: All flux data in the section of the table between double rules are based on extrapolated assumed calibration factors ($\lambda < 300$ Å) for GRD rocket monochromator flown on January 29, 1960, near noon from White Sands, New Mexico. Therefore the experimental accuracy of these data remains undetermined. The experiment was performed under normal solar conditions (compare with summary that follows).

Summary Reference for $\lambda < 200$ Å

λ or λ_1/λ_2 , Å	$h\nu$, ev	Estimated for Top of Atmosphere August 1960		h^* Estimated, $\Phi^* = \Phi_0/e$, $\cos Z = 1$, km	Number of Ion Pairs per Absorbed Photon	Solar Activity	Remarks
		Φ_0 , ph/cm ² sec	I_0 , erg/cm ² sec				
200/44	61/280	5 ⁸ -5 ⁹ up to 5 ¹⁰	0.1-1 up to 9	<140	~2 to 10	Normal Flares (class 2+)	From NRL photoionization mea- surements with different filters and assum- ing gray body radiation of $T \sim 5-7 \times 10^5$ deg K [Kreplin].
60/44	205/280	5 ⁷ -5 ⁸ up to 5 ⁹	0.02-0.17 up to 1.7	<100	~6 to 10	Normal Flares	Same source of data; $T \sim 5 \times 10^5$ deg K.
105/60	120/205	~1.5 ⁸	~0.35	~110	~4 to 6	Normal	GRD 1/29/60 experiment (see above).
20-8	620/520	4 ⁸ -2 ⁷ up to 1 ⁹	4 ⁻⁴ -2 ⁻² up to >0.9	85-105	~20 to 50	Normal Flares	NRL data with $T \sim 2 \times 10^6$ deg K [Kreplin].
<8	>1500	<1 ⁸ up to >2 ⁸	~1 ⁻³ up to >0.2	<90	>50	Normal Flares	NRL data 1949/60 (enhances D- region ionization during flares).

TABLE 16

COMPOSITION AND ENERGY SPECTRUM OF COSMIC RAYS

Charge (Z)	Range of Validity (E_t in Bev per nucleon)	Integral Spectrum (particles/m ² ·sec·ster)	
		Best Value	Extreme limits of exponent
1	2 - 20	$4000E_t^{-1.15}$	$1.05 - 1.25^*$
2	1.5 - 8	$450E_t^{-1.6}$	$1.3 - 1.7$
3, 4, 5	---	$\approx 50\%$ of C, N, O, F flux	
6, 7, 8, 9	3 - 8	$24E_t^{-1.6}$	$1.45 - 1.75$
≥ 10	3 - 8	$16E_t^{-2.0}$	$1.85 - 2.25$

*Slope increases up to 1.8 at higher energies

$$P(> E_t) = CE_t^{-1.5}/m^2\text{sec-ster} \quad (\text{Low energies})$$

protons $C = 3800$

alpha 370

Li, Be, B ≤ 14

C, N, O, F 21

$Z \geq 10$ 10

TABLE 17

PARAMETERS OF MICROMETEORITES

Visual Magnitude	Mass (g)	Radius (μ)	Velocity (km/sec)	Kinetic Energy (ergs)	No. Striking 3-m Sphere per Day	Flux (particle/cm ² -sec)
0	25.0	49,200	28	1.0×10^{14}		
1	9.95	36,200	28	3.98×10^{13}		
2	3.96	26,600	28	1.58×10^{13}		
3	1.58	19,600	28	6.31×10^{12}		
4	0.628	14,400	28	2.51×10^{12}		
5	0.250	10,600	28	1.00×10^{12}	2.22×10^{-5}	1.83×10^{-15}
6	9.95×10^{-2}	7,800	28	3.98×10^{11}	6.48×10^{-5}	5.34×10^{-15}
7	3.96×10^{-2}	5,740	28	1.58×10^{11}	1.63×10^{-4}	1.34×10^{-14}
8	1.58×10^{-2}	4,220	27	5.87×10^{10}	4.09×10^{-4}	3.36×10^{-14}
9	6.28×10^{-3}	3,110	26	2.17×10^{10}	1.03×10^{-3}	8.49×10^{-14}
10	2.50×10^{-3}	2,290	25	7.97×10^9	2.58×10^{-3}	2.12×10^{-13}
11	9.95×10^{-4}	1,680	24	2.93×10^9	6.48×10^{-3}	5.34×10^{-13}
12	3.96×10^{-4}	1,240	23	1.07×10^9	1.63×10^{-2}	1.34×10^{-12}
13	1.58×10^{-4}	910	22	3.89×10^8	4.09×10^{-2}	3.36×10^{-12}
14	6.28×10^{-5}	669	21	1.41×10^8	1.03×10^{-1}	8.49×10^{-12}
15	2.50×10^{-5}	492	20	5.10×10^7	2.58×10^{-1}	2.12×10^{-11}
16	9.95×10^{-6}	362	19	1.83×10^7	6.48×10^{-1}	5.34×10^{-11}
17	3.96×10^{-6}	266	18	6.55×10^6	1.63	1.34×10^{-10}
18	1.58×10^{-6}	196	17	2.33×10^6	4.09	3.36×10^{-10}
19	6.28×10^{-7}	144	16	8.20×10^5	1.03×10	8.49×10^{-10}
20	2.50×10^{-7}	106	15	2.87×10^5	2.58×10	2.12×10^{-9}
21	9.95×10^{-8}	78.0	15	1.14×10^5	6.48×10	5.34×10^{-9}
22	3.96×10^{-8}	57.4	15	4.55×10^4	1.63×10^2	1.34×10^{-8}
23	1.58×10^{-8}	39.8 ^a	15	1.81×10^4	4.09×10^2	3.36×10^{-8}
24	6.28×10^{-9}	25.1 ^a	15	7.21×10^3	1.03×10^3	8.49×10^{-8}
25	2.50×10^{-9}	15.8 ^a	15	2.87×10^3	2.58×10^3	2.12×10^{-7}
26	9.95×10^{-10}	10.0 ^a	15	1.14×10^3	6.48×10^3	5.34×10^{-7}
27	3.96×10^{-10}	6.30 ^a	15	4.55×10^2	1.63×10^4	1.34×10^{-6}
28	1.58×10^{-10}	3.98 ^a	15	1.81×10^2	4.09×10^4	3.35×10^{-6}
29	6.28×10^{-11}	2.51 ^a	15	7.21×10	1.03×10^5	8.49×10^{-6}
30	2.50×10^{-11}	1.58 ^a	15	2.87×10	2.58×10^5	2.12×10^{-5}
31	9.95×10^{-12}	1.00 ^a	15	1.14×10	6.48×10^5	5.34×10^{-5}

^a Maximum radius permitted by solar light pressure.

TABLE 18

METEOR STREAMS

Shower	Date of Maximum	Limits	Radiant		Ve- locity (km/sec)	Maximum Hourly Radar Echo Rate
			R.A. (°)	Dec. (°)		
Quadrantids	Jan 3	Jan 1-Jan 4	230	+48	42.7	95
Virginids	Mar 13	Mar 5-Mar 21	183	+ 4	30.8	<5
Lyrids	Apr 21	Apr 20-Apr 23	270	+33	48.4	11
η Aquarids	May 4	May 2-May 6	336	+ 0	64	15
Daytime Arietids	June 8	May 29-June 18	44	+23	39	66
Daytime ξ Perseids	June 9	June 1-June 16	62	+23	29	42
Sagittarids	June 11		304	-35		30
Daytime β Taurids	June 30	June 24-July 6	86	+19	32	27
Phoenicids	July 14		32	-48		30
Southern δ Aquarids	July 30	July 21-Aug 15	339	-17	43.0	34
Northern δ Aquarids		July 14-Aug 19	339	- 5	42.3	
Southern ι Aquarids		July 16-Aug. 25	338	-14	35.8	
Northern ι Aquarids		July 16-Aug 25	331	- 5	31.2	
α Capricornids	Aug 1	July 17-Aug 21	309	-10	25.5	10
Perseids	Aug 12	July 29-Aug 17	46	+58	60.4	49
α Cygnids		Aug 19-Aug 22	289	+56	26.6	<5
Draconids	Oct 10	Oct 10	264	+54	23.1	Periodic
Orionids	Oct 22	Oct 18-Oct 26	94	+16	66.5	18
Southern Taurids	Nov 1	Sept. 15-Dec 15	51	+14	30.2	<15
Northern Taurids	Nov 1	Oct 17-Dec 2	52	+21	31.3	
Andromedids	Nov 7	Nov 7	22	+27	21.3	<5
Leonids	Nov 17	Nov 14-Nov 20	152	+22	72.0	<10
Puppids/Velids	Dec 6	Dec 1-Dec 9	140	-50		50
Geminids	Dec 14	Dec 7-Dec 15	113	+32	36.5	80
χ Orionids		Dec 9-Dec 14	87	+21	30.6	
Monocerotids		Dec 13-Dec 15	103	+ 8	44.0	
Ursids	Dec 22	Dec 17-Dec 24	206	+80	35.2	13

TABLE 19

Direct Measurements Obtained with Microphone Systems on the U. S. Satellites and Space Probes

Spacecraft	Momentum Sensitivity (dyne seconds)	Mass Sensitivity (grams)	Effective Area (meter ²)	Exposure Time (seconds)	Exposure (m ² sec)	Number of Particles	Cumulative Influx Rate (particles/m ² /sec)	
							Observed	Corrected for Earth Shielding
EXPLORER I	$> 2.5 \times 10^{-3}$	8.3×10^{-10}	2.3×10^{-1}	7.9×10^4	1.8×10^4	145	8.4×10^{-3}	1.7×10^{-2}
PIONEER I	$> 1.5 \times 10^{-4}$	5.0×10^{-11}	3.9×10^{-2}	1.1×10^5	4.2×10^3	25 (18)	4.3×10^{-3}	4.3×10^{-3}
VANGUARD III	$> 1.0 \times 10^{-2}$	3.3×10^{-9}	4.0×10^{-1}	$\sim 6 \times 10^6$	2.4×10^6	~ 3500	1.3×10^{-3}	2.0×10^{-3}

TABLE 20

Direct Measurements Obtained with Microphone Systems on the Soviet Satellites and Space Probes

Spacecraft	Mass Sensitivity (grams)		Effective Area (meter ²)	Exposure Time (seconds)	Exposure (m ² sec)	Number of Particles	Cumulative Influx Rate (particles/m ² /sec)
	$\bar{v}_G = 40 \text{ Km/sec}$	$\bar{v}_G = 30 \text{ Km/sec}$					
SPUTNIK III	$8.0 \times 10^{-9} - 2.7 \times 10^{-8}$ $2.7 \times 10^{-8} - 1.5 \times 10^{-7}$ $1.5 \times 10^{-7} - 5.6 \times 10^{-6}$ $> 5.6 \times 10^{-6}$	$1.4 \times 10^{-8} - 4.8 \times 10^{-8}$ $4.8 \times 10^{-8} - 2.7 \times 10^{-7}$ $2.7 \times 10^{-7} - 1.0 \times 10^{-5}$ $> 1.0 \times 10^{-5}$	0.34	$\sim 8 \times 10^5$	$\sim 3 \times 10^5$	?	$< 1 \times 10^{-4}$
SPACE ROCKET I	$2.5 \times 10^{-9} - 1.5 \times 10^{-8}$ $1.5 \times 10^{-8} - 2.0 \times 10^{-7}$ $> 2.0 \times 10^{-7}$	$4.4 \times 10^{-9} - 2.7 \times 10^{-8}$ $2.7 \times 10^{-8} - 3.6 \times 10^{-7}$ $> 3.6 \times 10^{-7}$	0.2	3.6×10^4	7.2×10^3	< 16 < 4 < 1	$< 2.9 \times 10^{-3}$ $< 7.0 \times 10^{-4}$ $< 1.4 \times 10^{-4}$
SPACE ROCKET II	$2.0 \times 10^{-9} - 6.0 \times 10^{-9}$ $6.0 \times 10^{-9} - 1.5 \times 10^{-8}$ $> 1.5 \times 10^{-8}$	$3.6 \times 10^{-9} - 1.1 \times 10^{-8}$ $1.1 \times 10^{-8} - 2.7 \times 10^{-8}$ $> 2.7 \times 10^{-8}$	0.2	1.1×10^5	2.2×10^4	0 0 2	9.1×10^{-5}
INTERPLANETARY STATION	$1.0 \times 10^{-9} - 3.0 \times 10^{-9}$ $3.0 \times 10^{-9} - 8.0 \times 10^{-9}$ $> 8.0 \times 10^{-9}$	$1.8 \times 10^{-9} - 5.3 \times 10^{-9}$ $5.3 \times 10^{-9} - 1.4 \times 10^{-8}$ $> 1.4 \times 10^{-8}$	0.1	2.3×10^4	2.3×10^3	1 5 1	3.0×10^{-3} 2.6×10^{-3} 4.3×10^{-4}

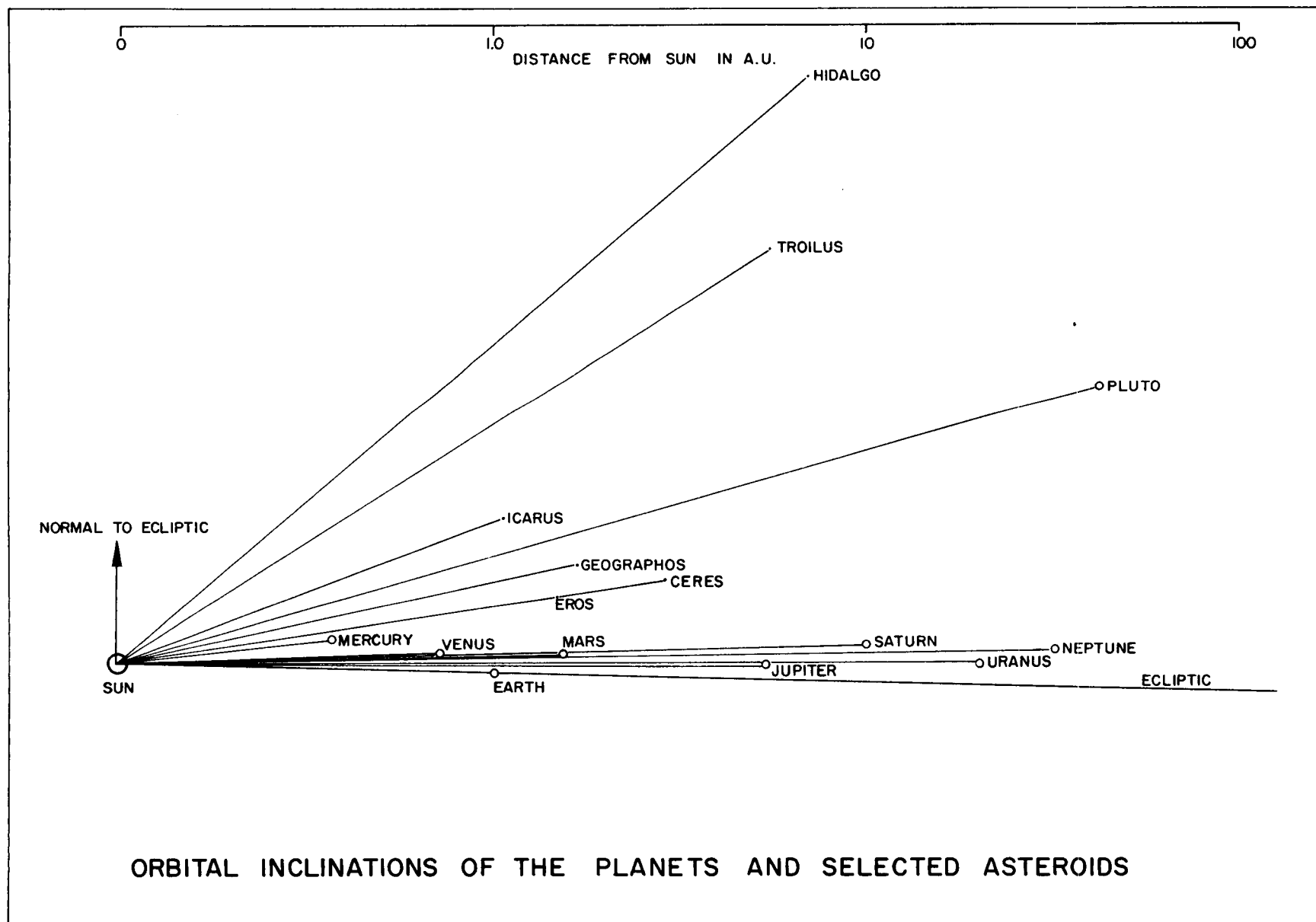


Figure 1

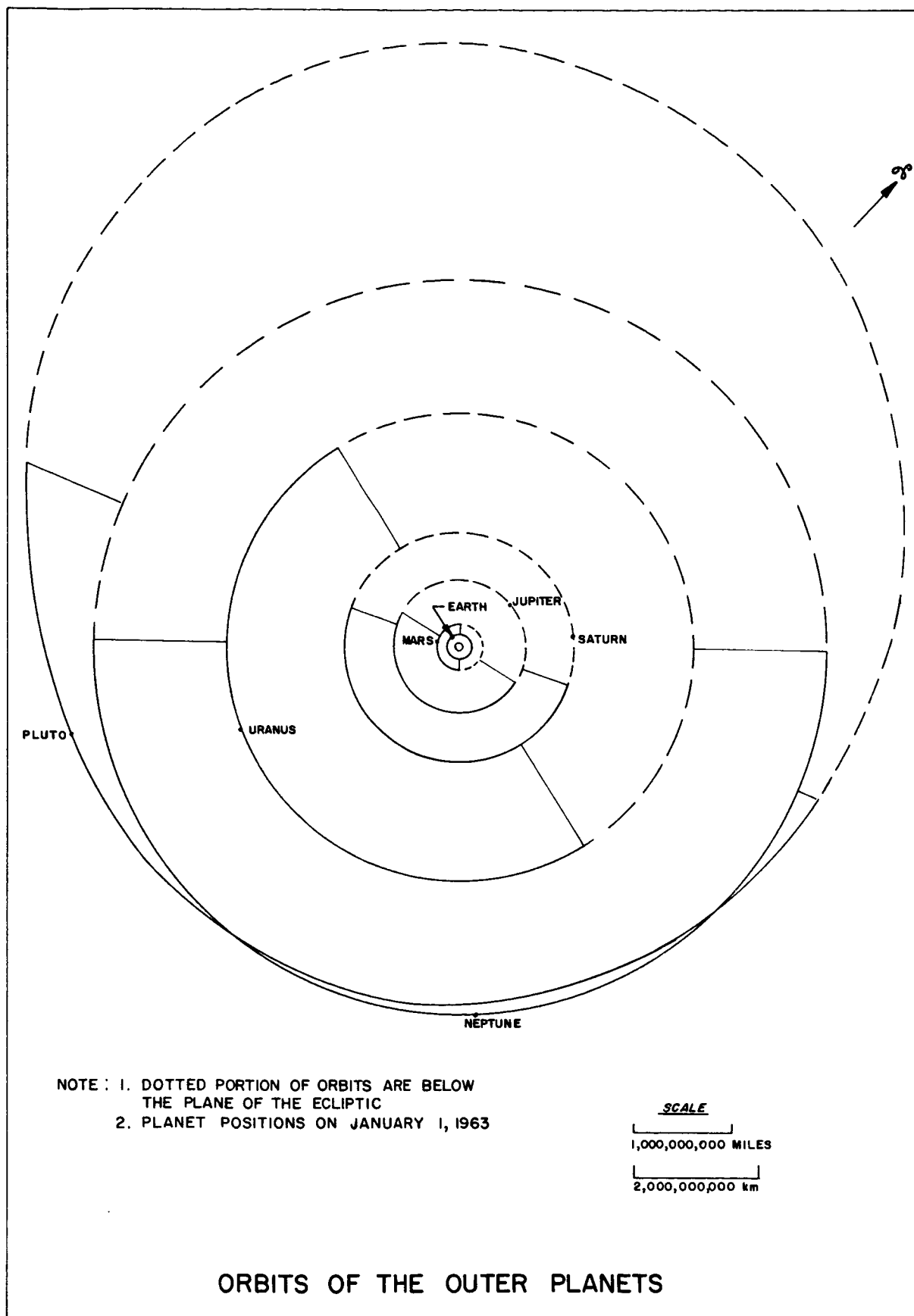


Figure 2

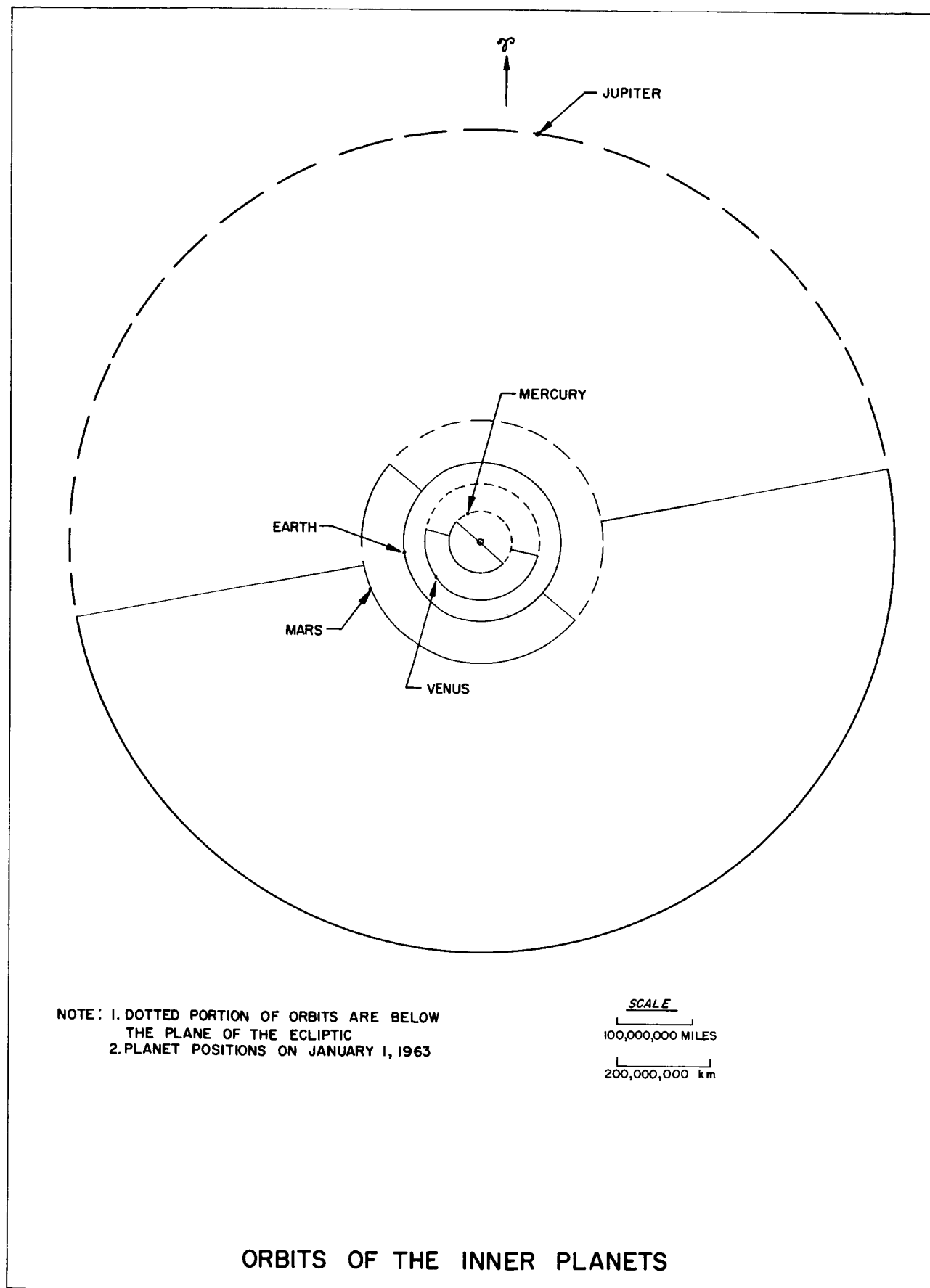


Figure 3

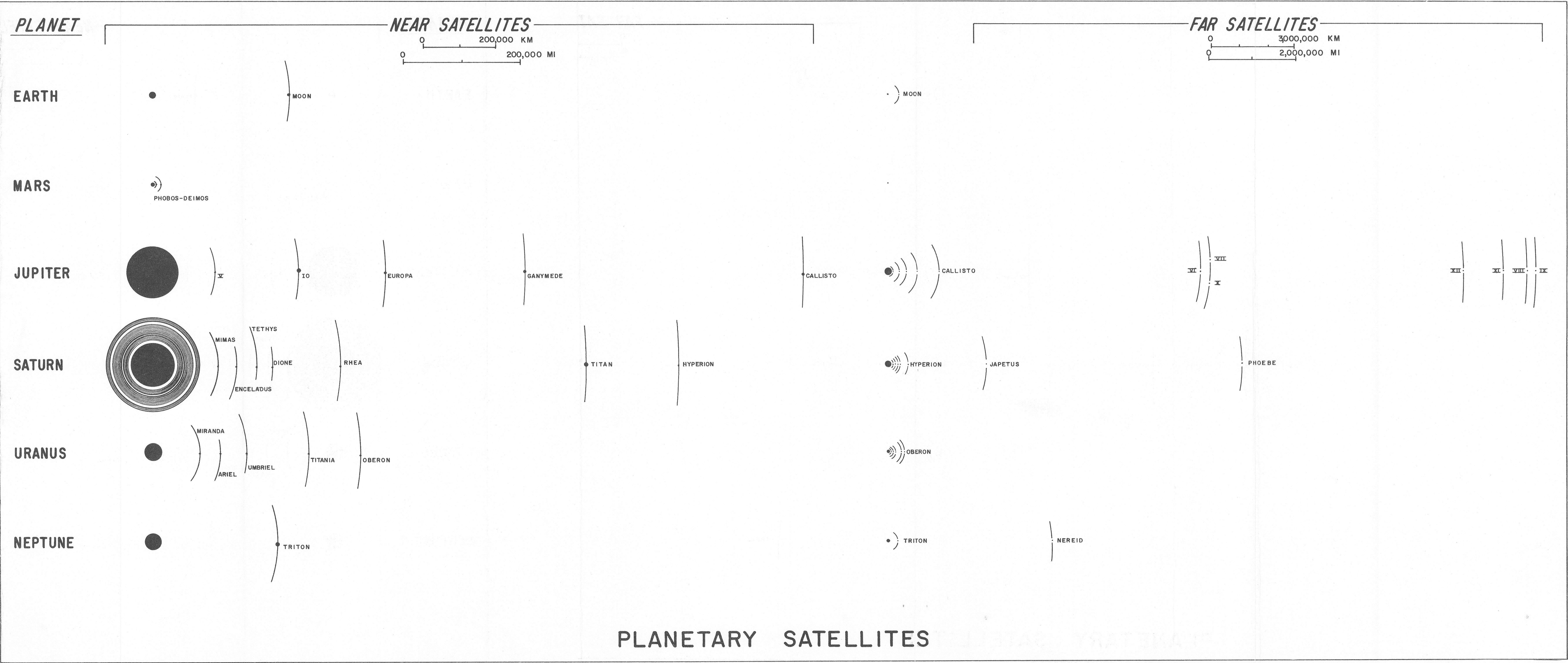
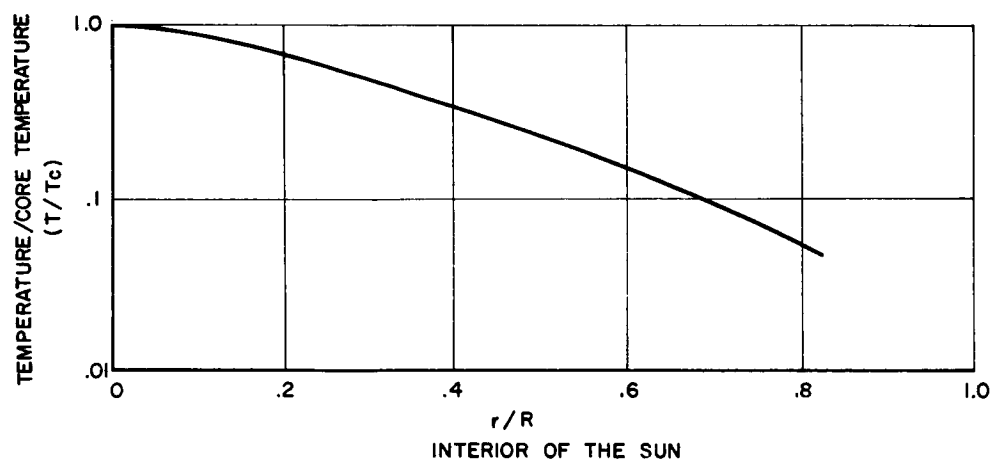
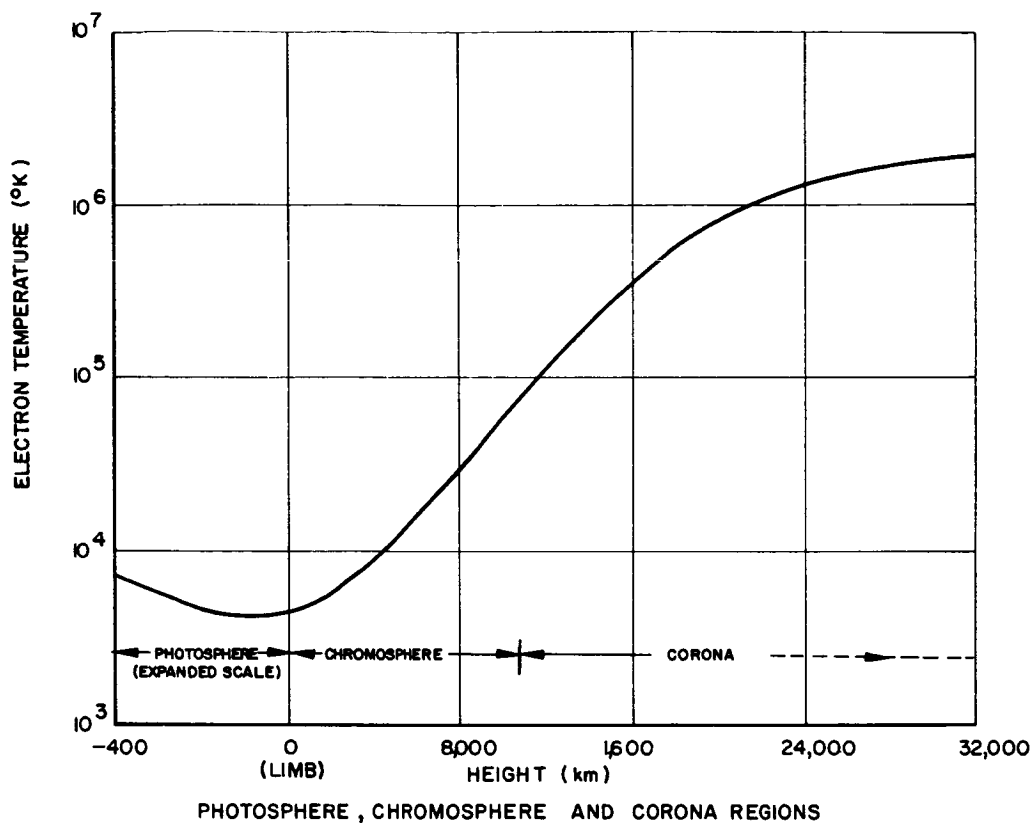


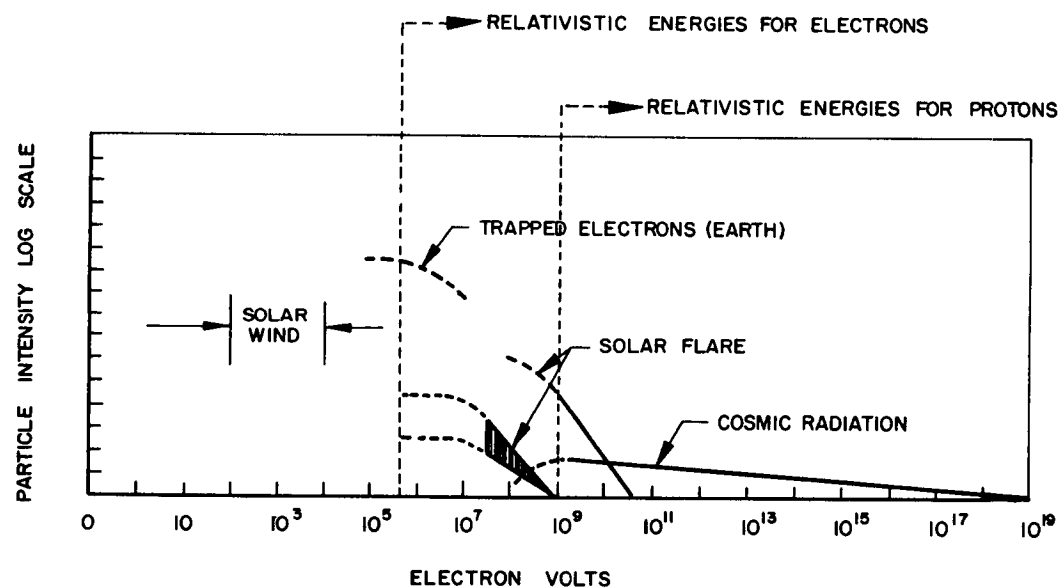
Figure 4



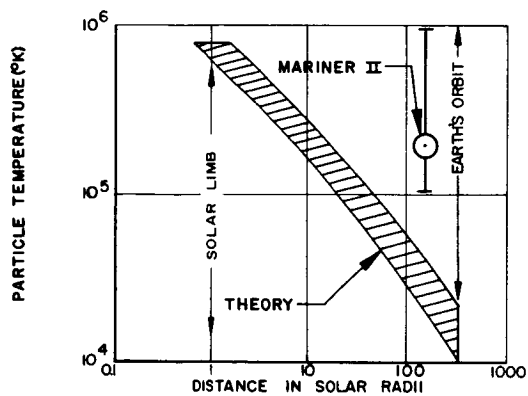
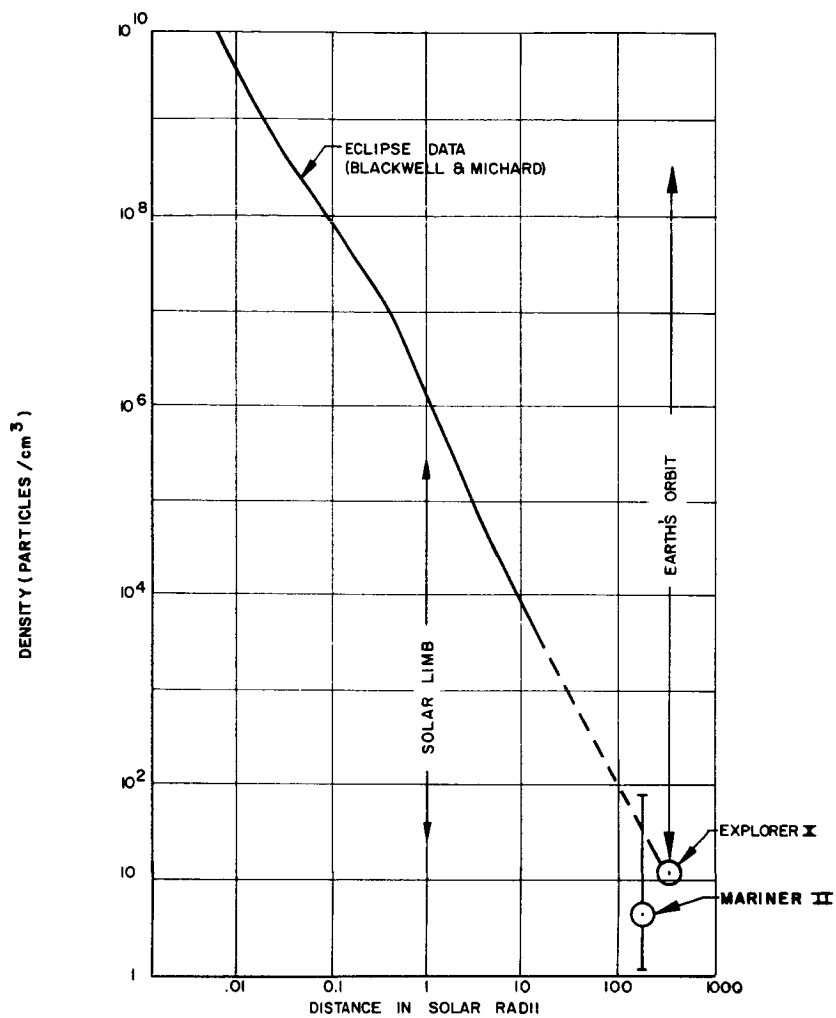
SOLAR TEMPERATURE DISTRIBUTION

Figure 5

Figure 6



ENERGETIC PARTICLES OBSERVED IN THE SOLAR SYSTEM



ELECTRON DENSITY AND TEMPERATURE IN SPACE

Figure 7

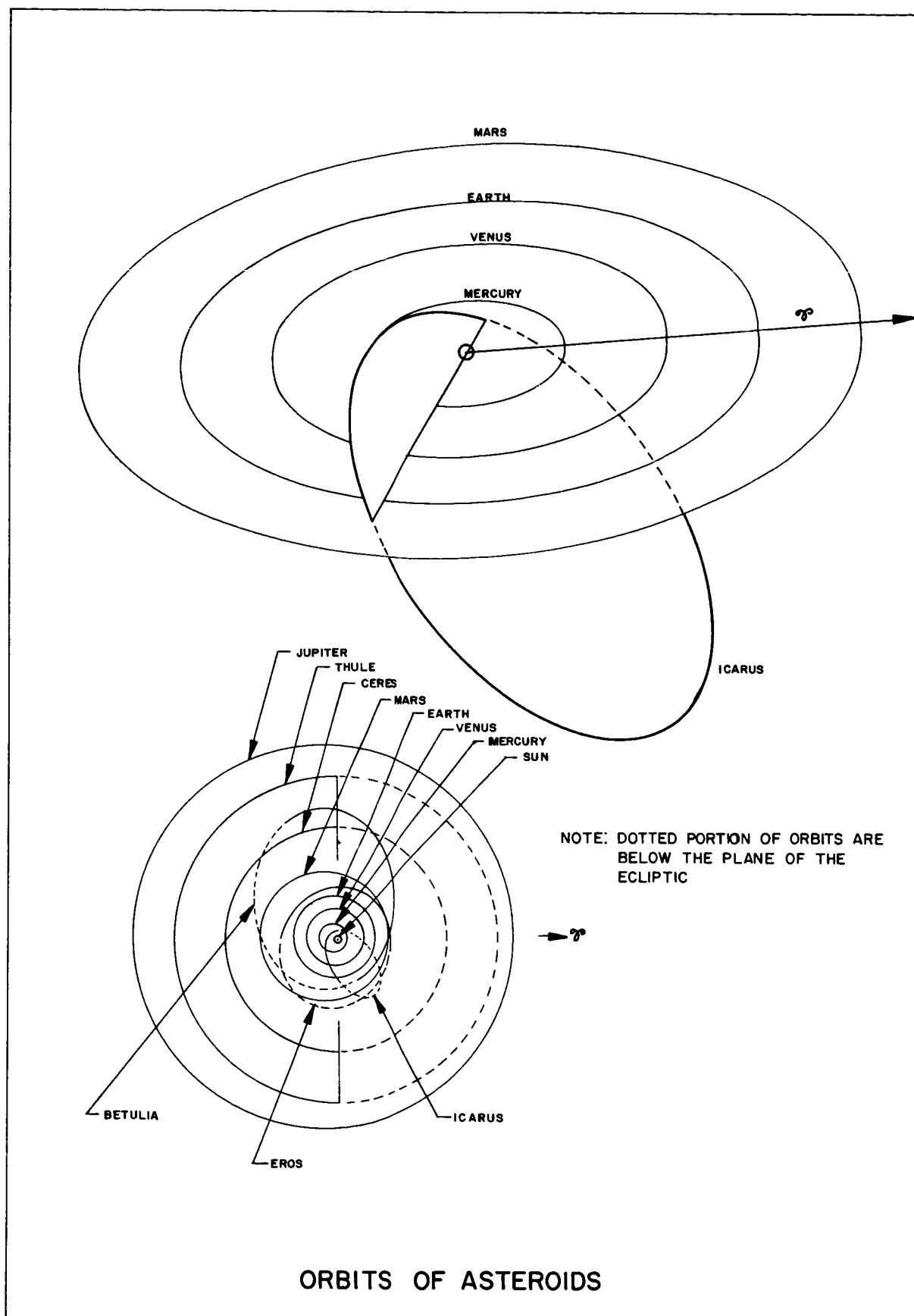


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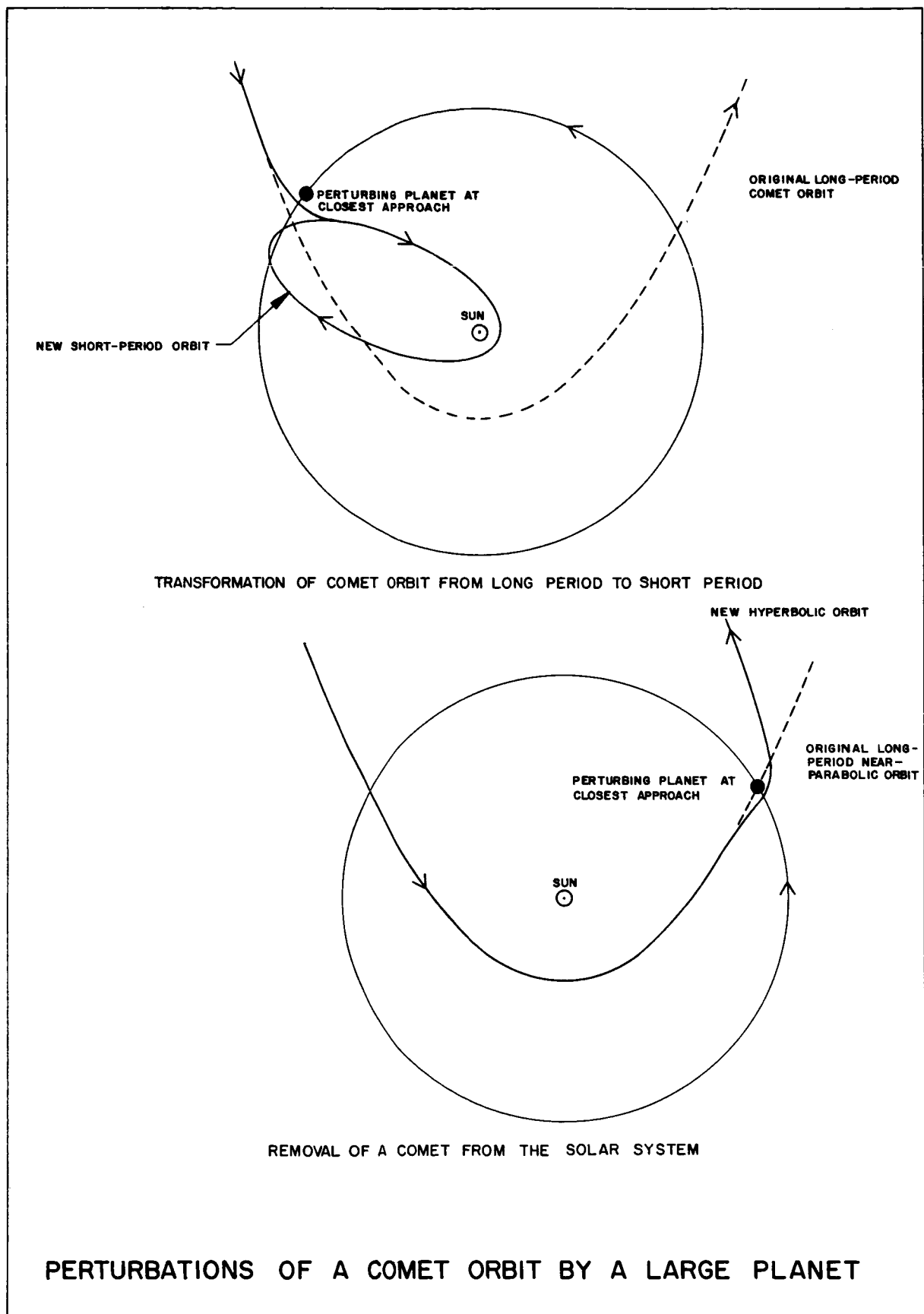
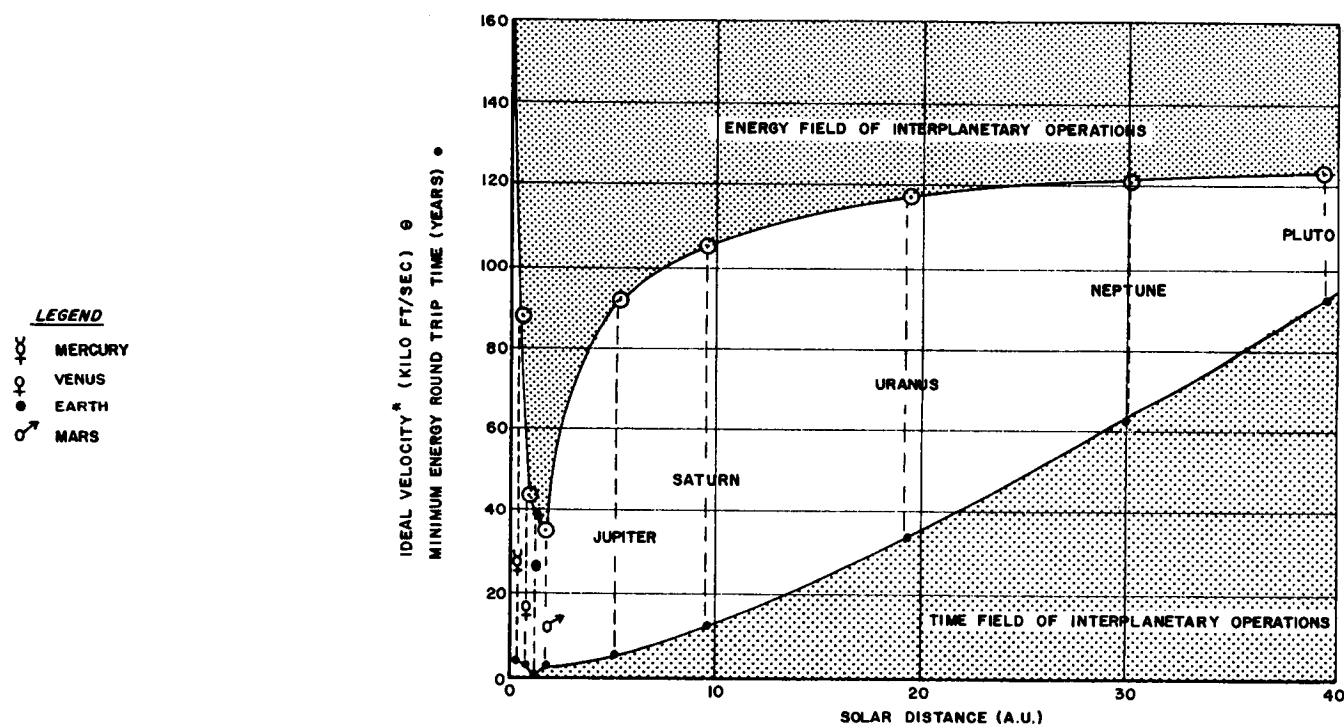


Figure 9

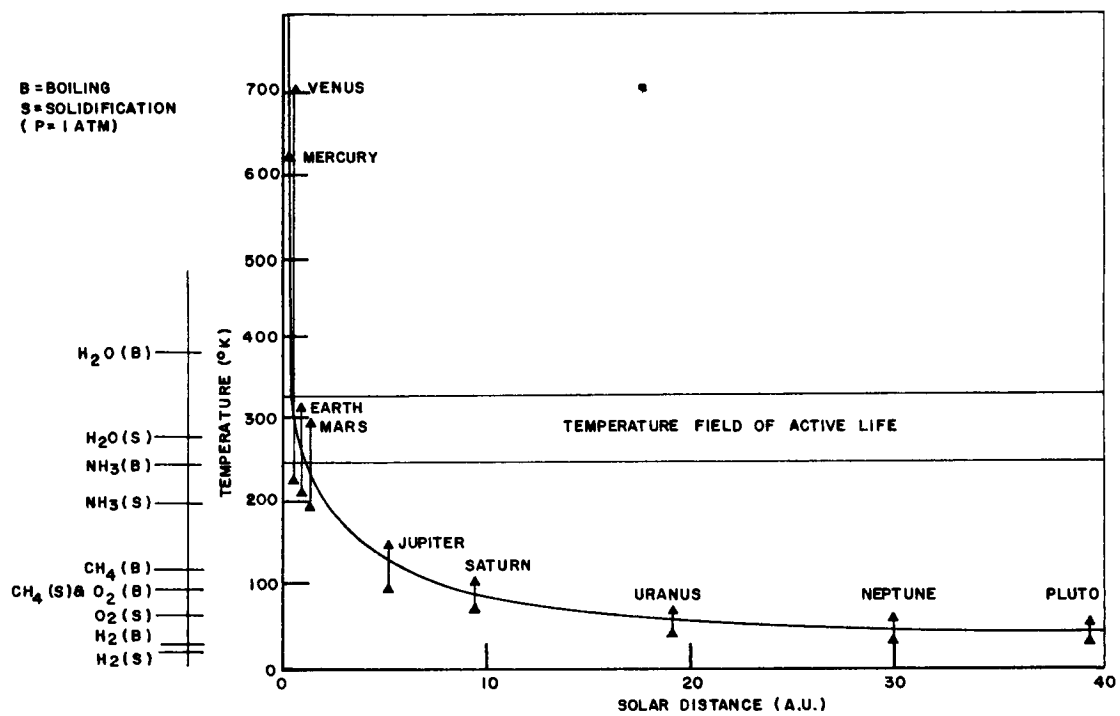
Figure 10



* THE VELOCITY WHICH BURN-OUT STAGE WOULD ATTAIN IF IT USED UP ALL ENERGY REQUIRED FOR THE ROUND TRIP IN ONE IMPULSE BURST

TIME AND VELOCITY REQUIRED FOR SPACE MISSIONS

Figure 11



PLANETARY TEMPERATURES

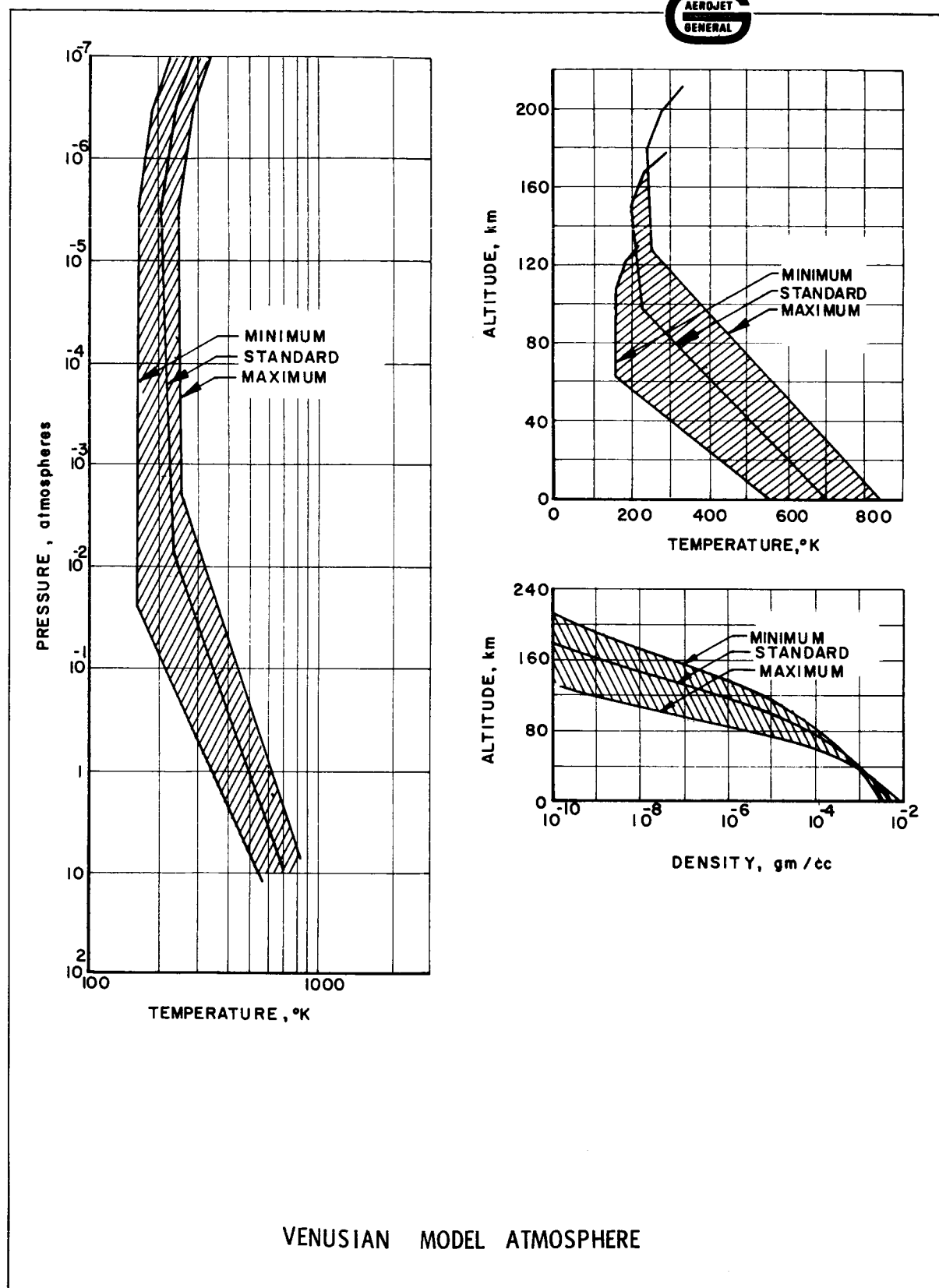


Figure 12

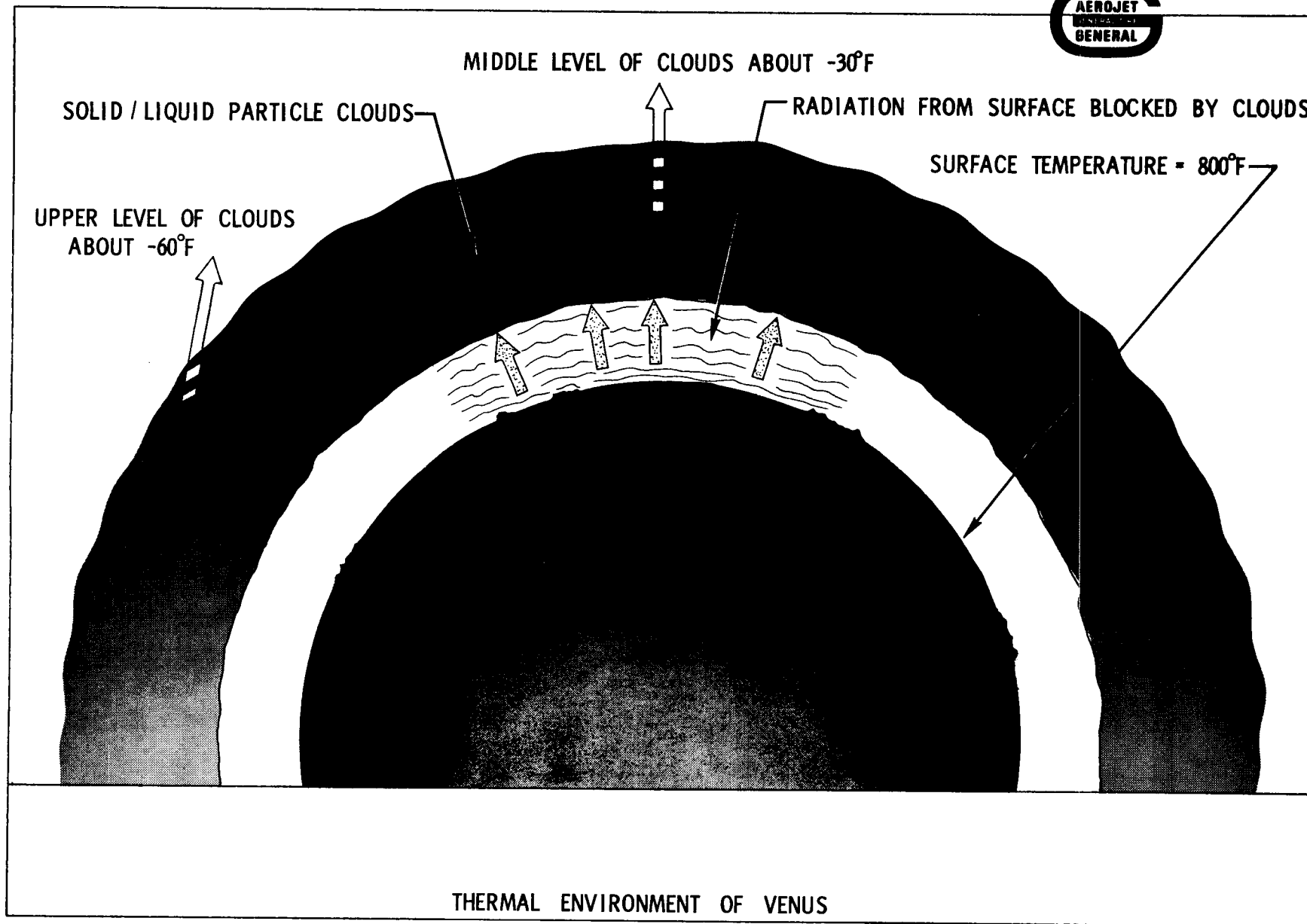
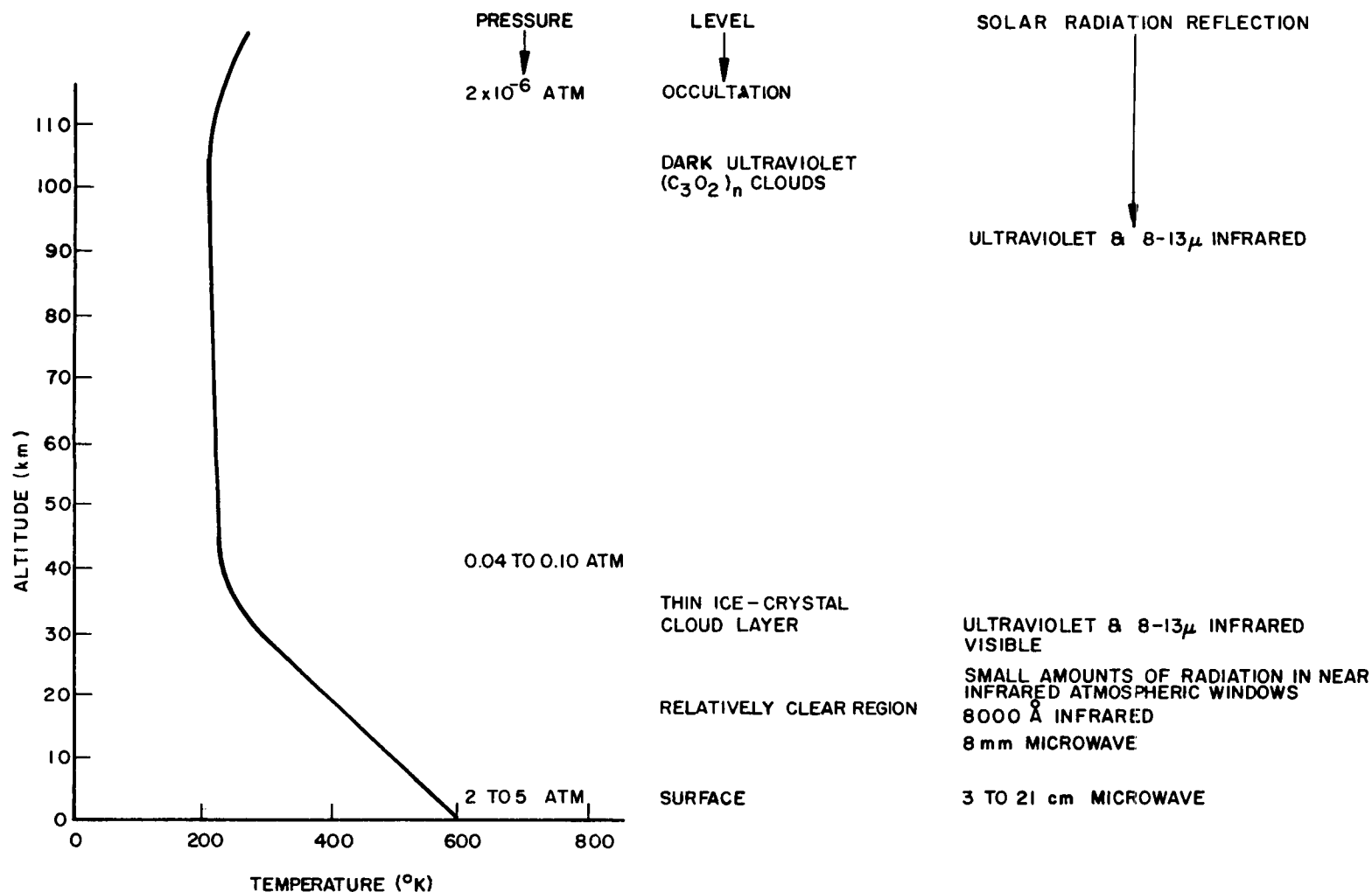
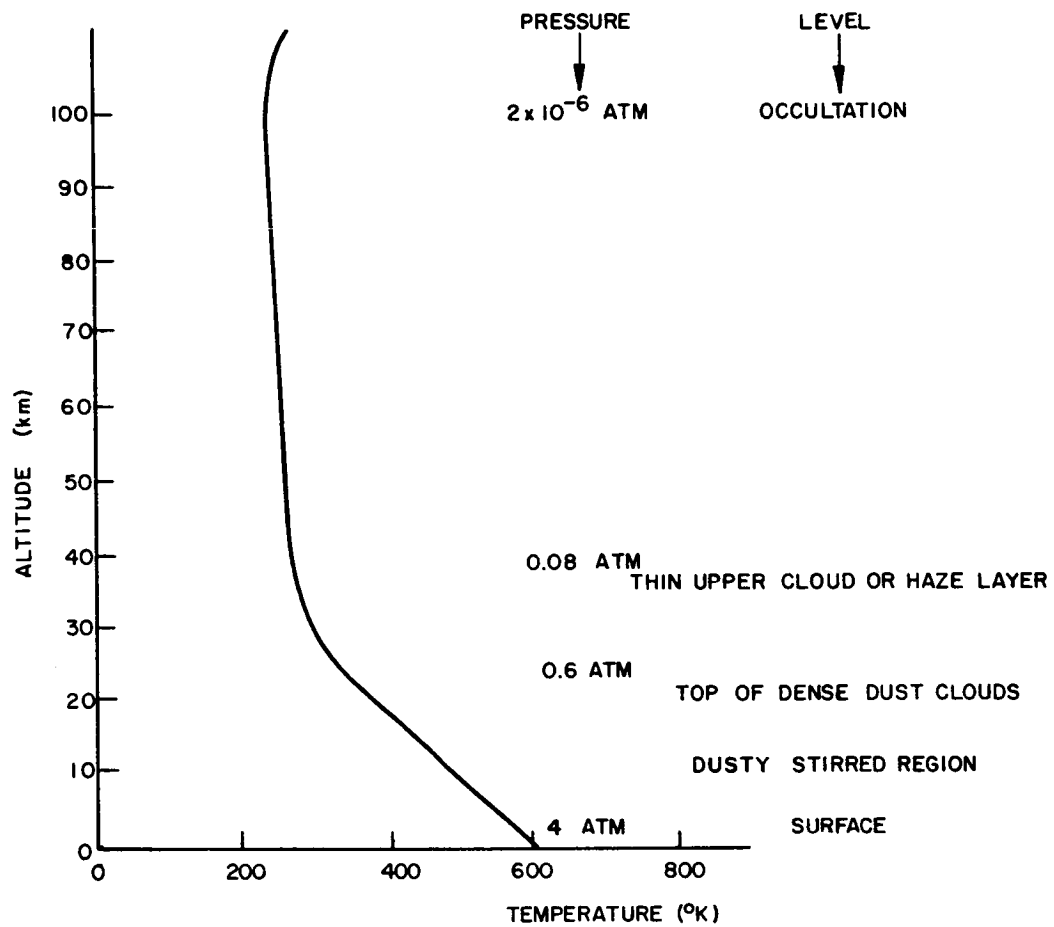


Figure 13

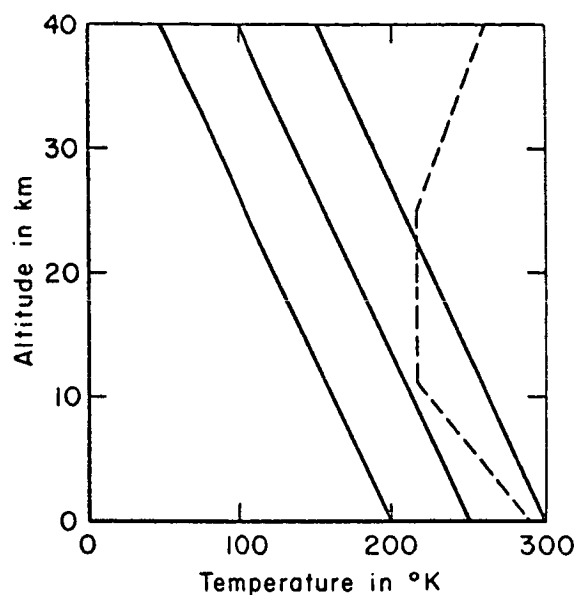


GREENHOUSE MODEL OF THE VENUSIAN ATMOSPHERE

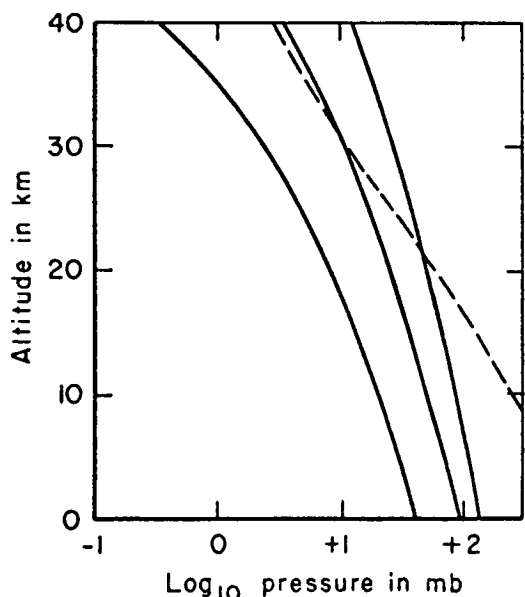


AEOLOSHERE MODEL OF THE VENUSIAN ATMOSPHERE

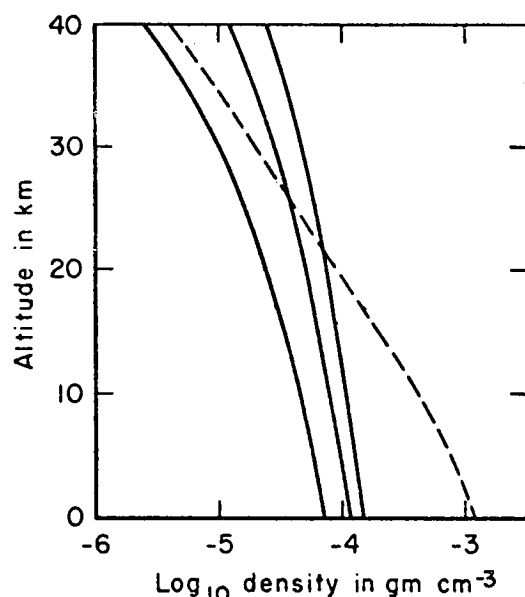
Figure 15



A—Variation of temperature extremes with altitude



B—Variation of pressure extremes with altitude

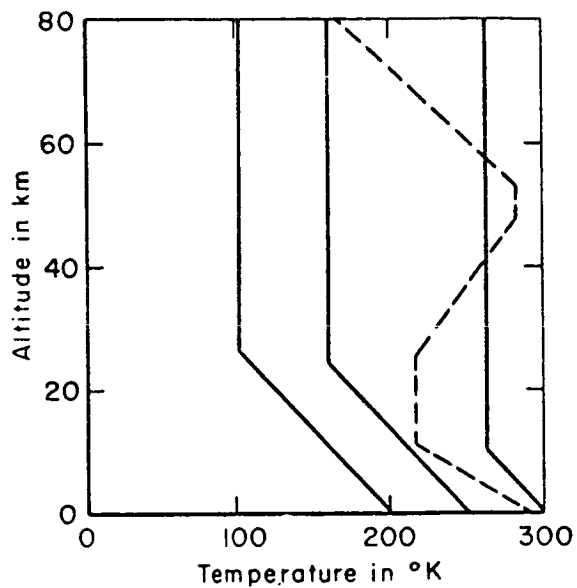


C—Variation of density extremes with altitude

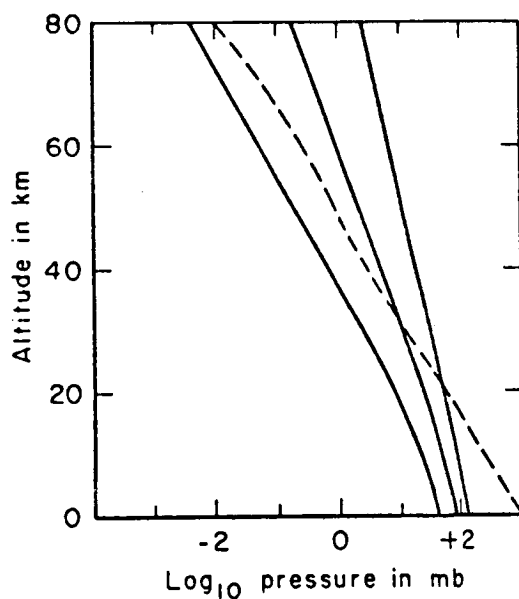
Earth ARDC 1959 model atmosphere in dashed lines.

Model I Mars atmosphere
Convective equilibrium throughout

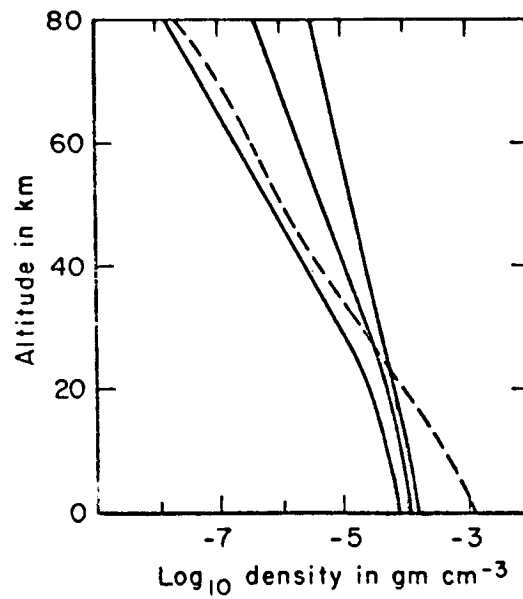
Figure 16



A—Variations of temperature extremes with altitude



B—Variation of pressure extremes with altitude

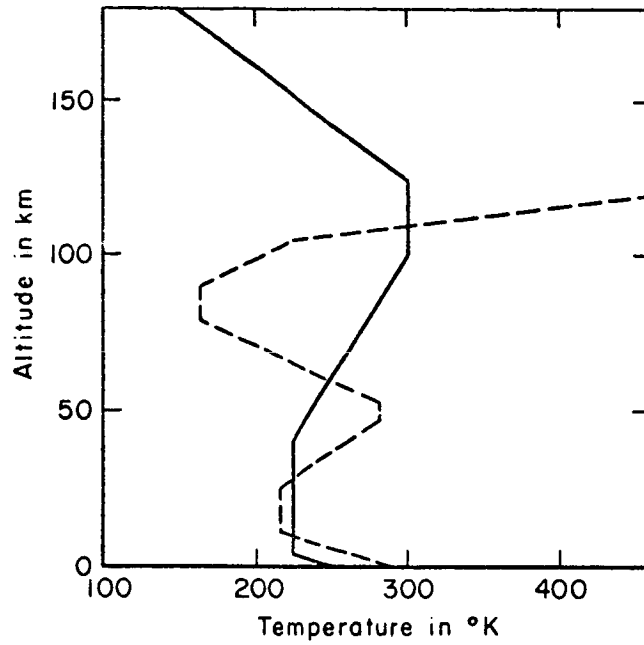


C—Variation of density extremes with altitude

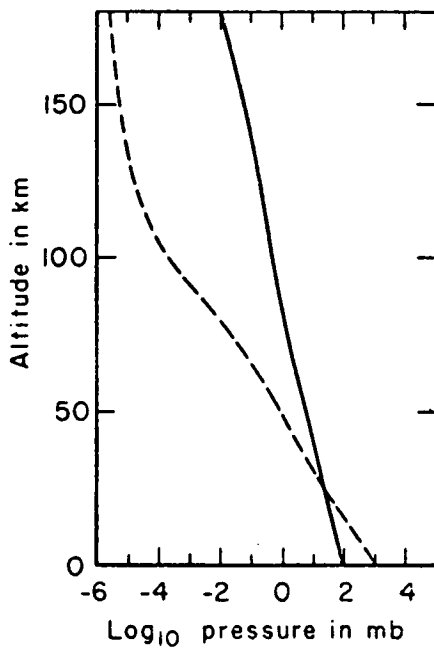
Earth ARDC 1959 model atmosphere in dashed lines.

Model II Mars atmosphere

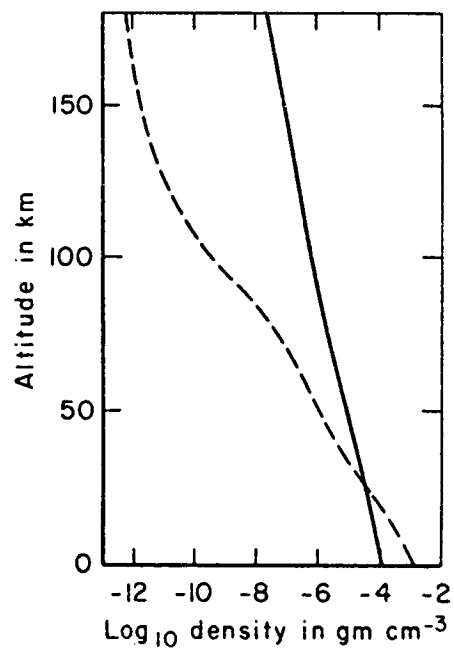
Convective equilibrium to assumed tropopause level, and conductive equilibrium above



A — Variation of temperature with altitude



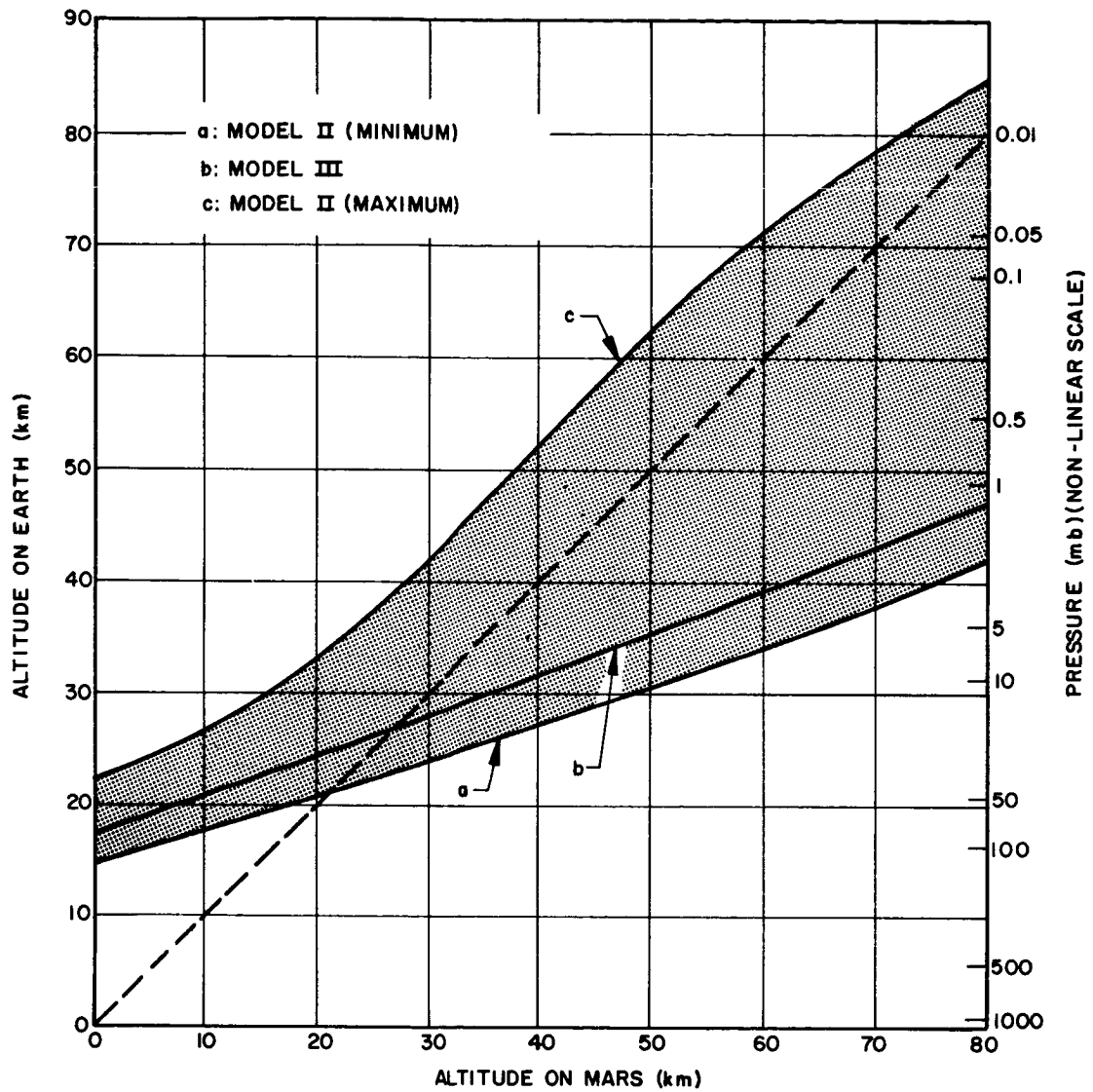
B — Variation of pressure with altitude



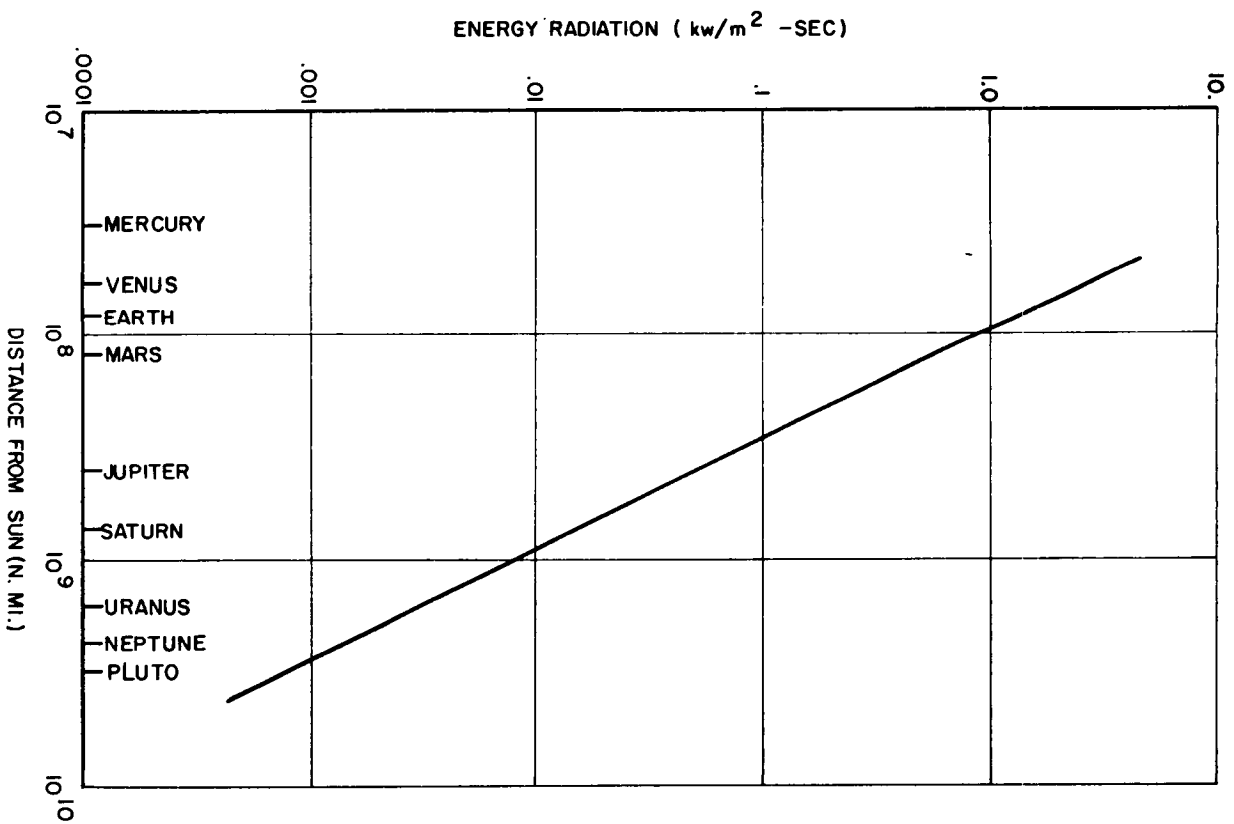
C — Variation of density with altitude

Earth ARDC 1959 model atmosphere in dashed lines

Conjectural model III Mars atmosphere

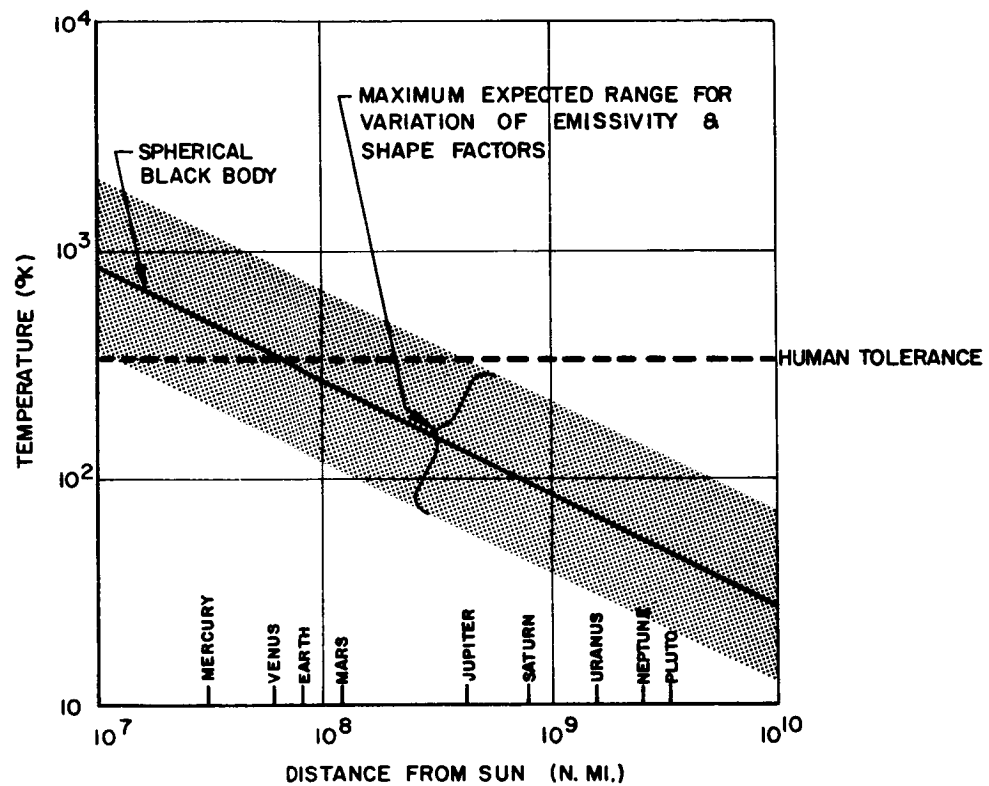


EXTREME RANGES OF EQUAL PRESSURE
ALTITUDES FOR EARTH AND MARS

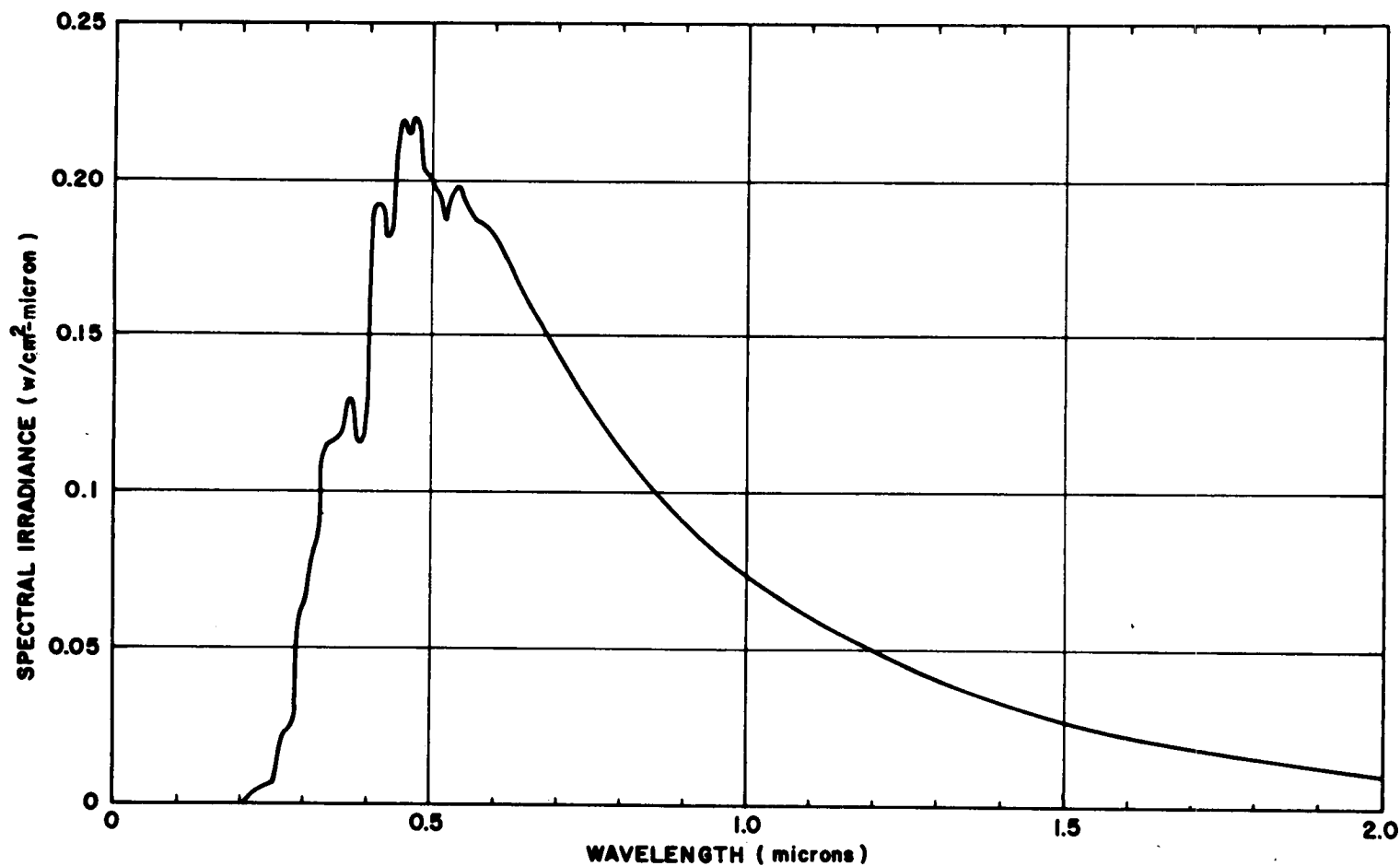


RADIATION ENERGY FIELD OF THE SUN

Figure 20



RADIATION EQUILIBRIUM TEMPERATURES FOR A
SPHERICAL BLACK BODY IN SPACE



SOLAR SPECTRAL IRRADIANCE ABOVE THE EARTH'S ATMOSPHERE AT THE EARTH'S MEAN DISTANCE FROM THE SUN

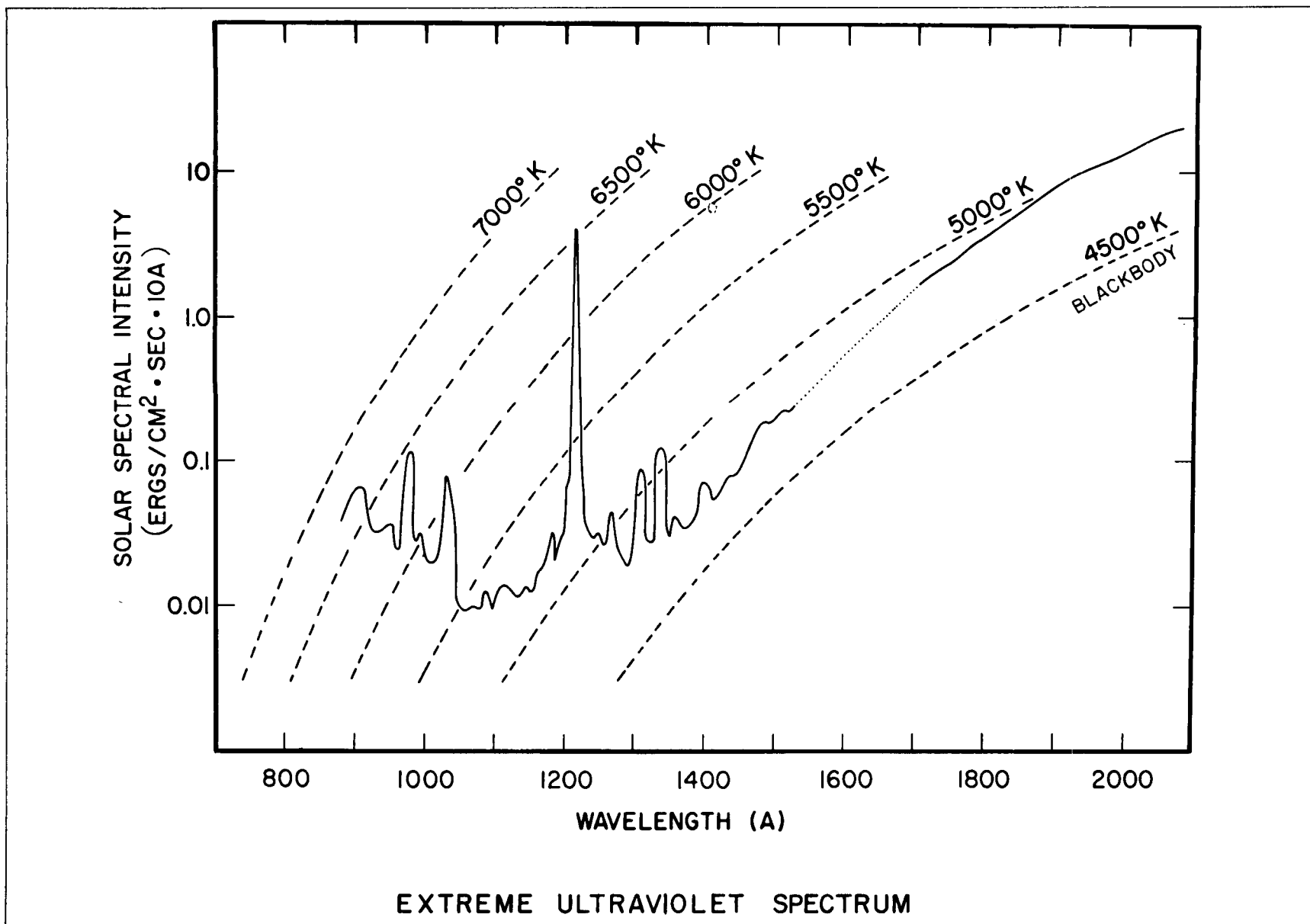
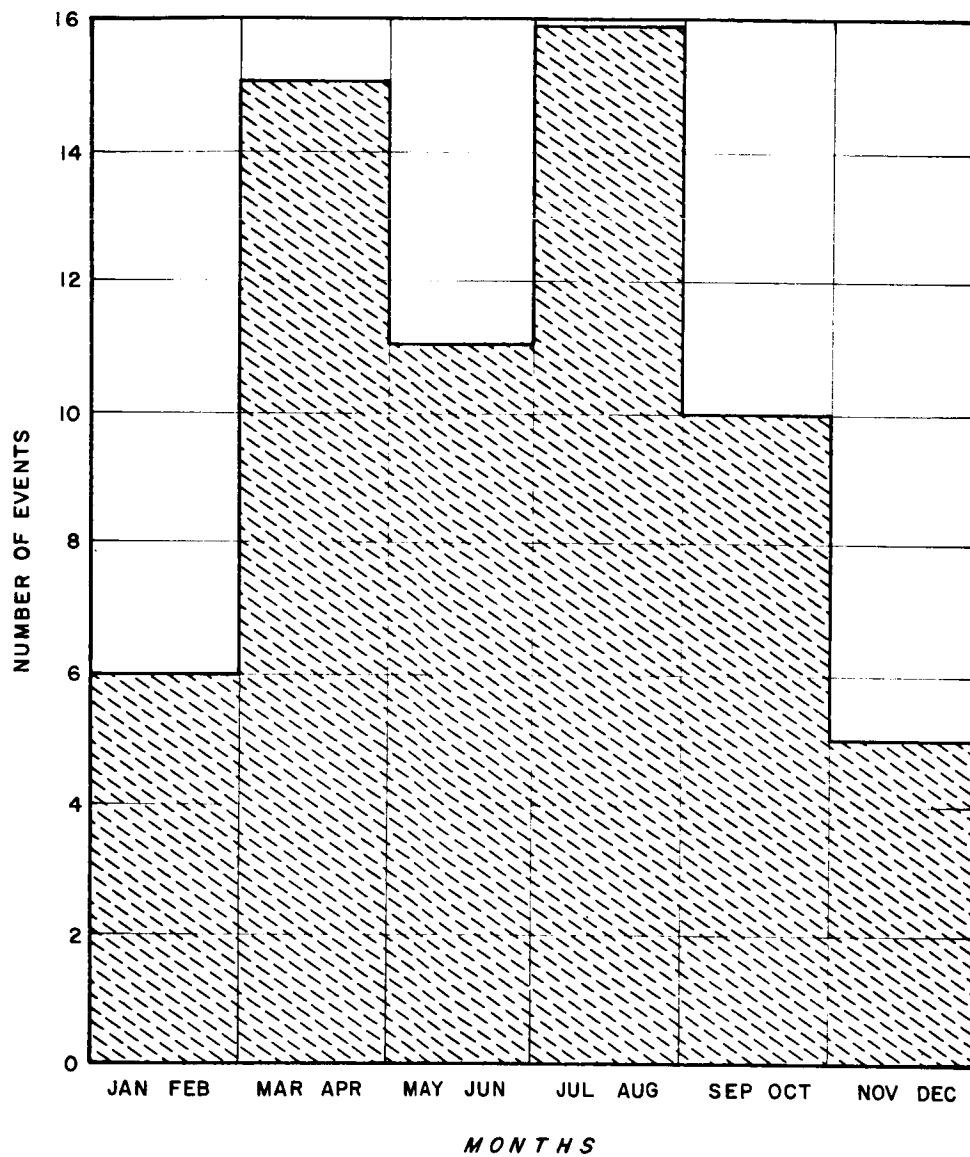
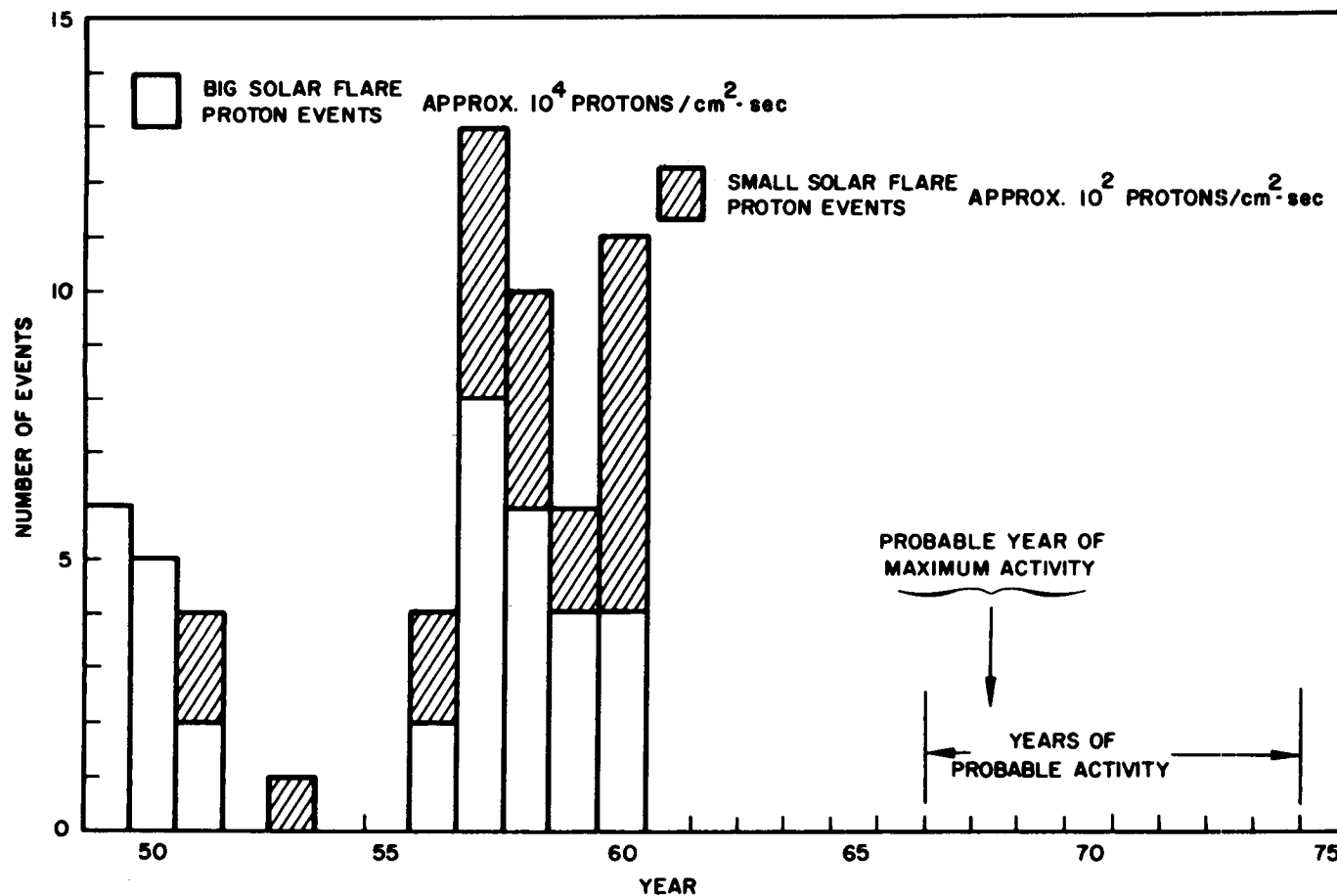


Figure 23



BI - MONTHLY DISTRIBUTION OF POLAR CAP ABSORPTION EVENTS
FOR THE PERIOD 1949 TO 1960



FREQUENCY OF SOLAR-FLARE PROTON IMPINGEMENT ON THE POLAR CAP

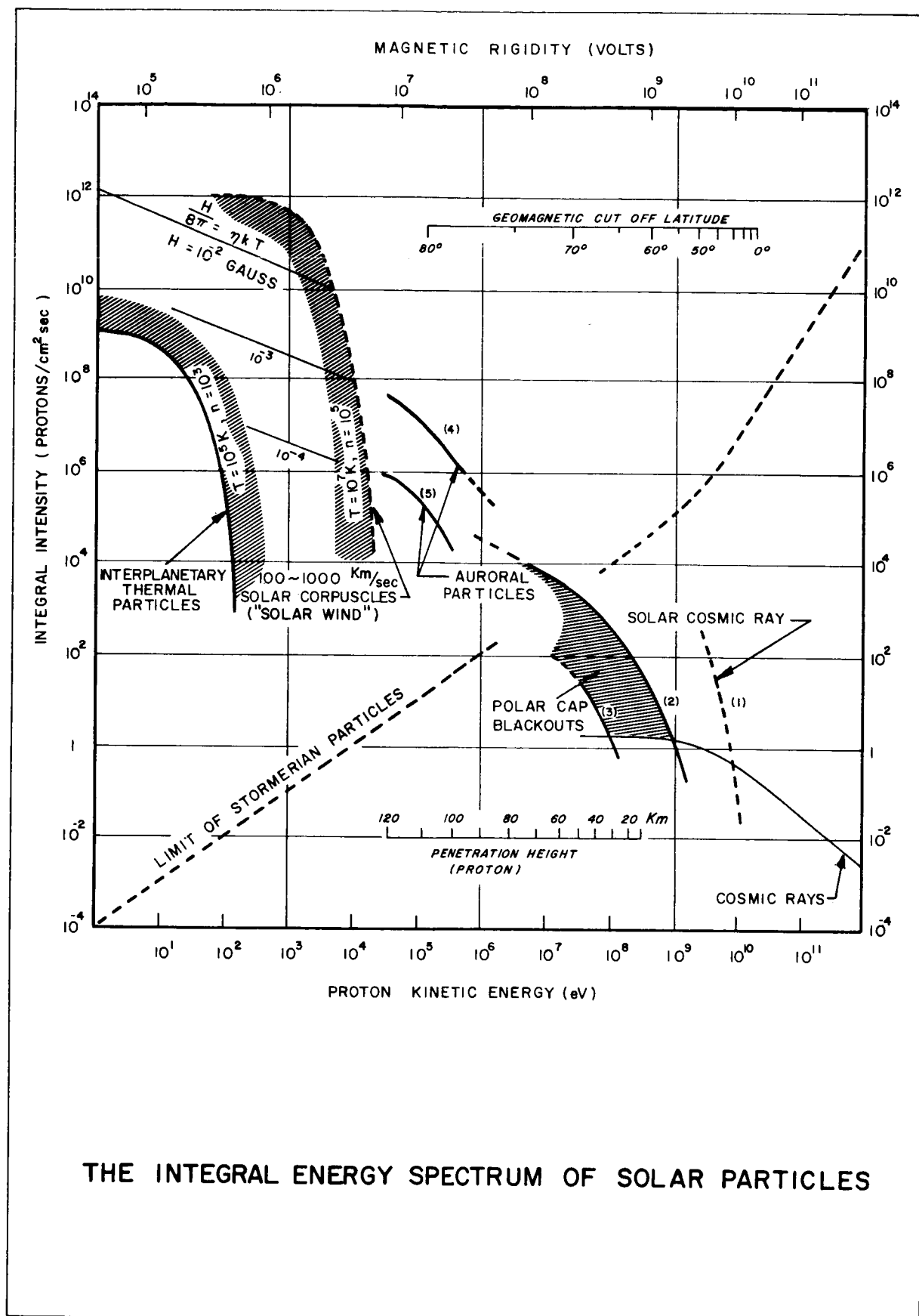
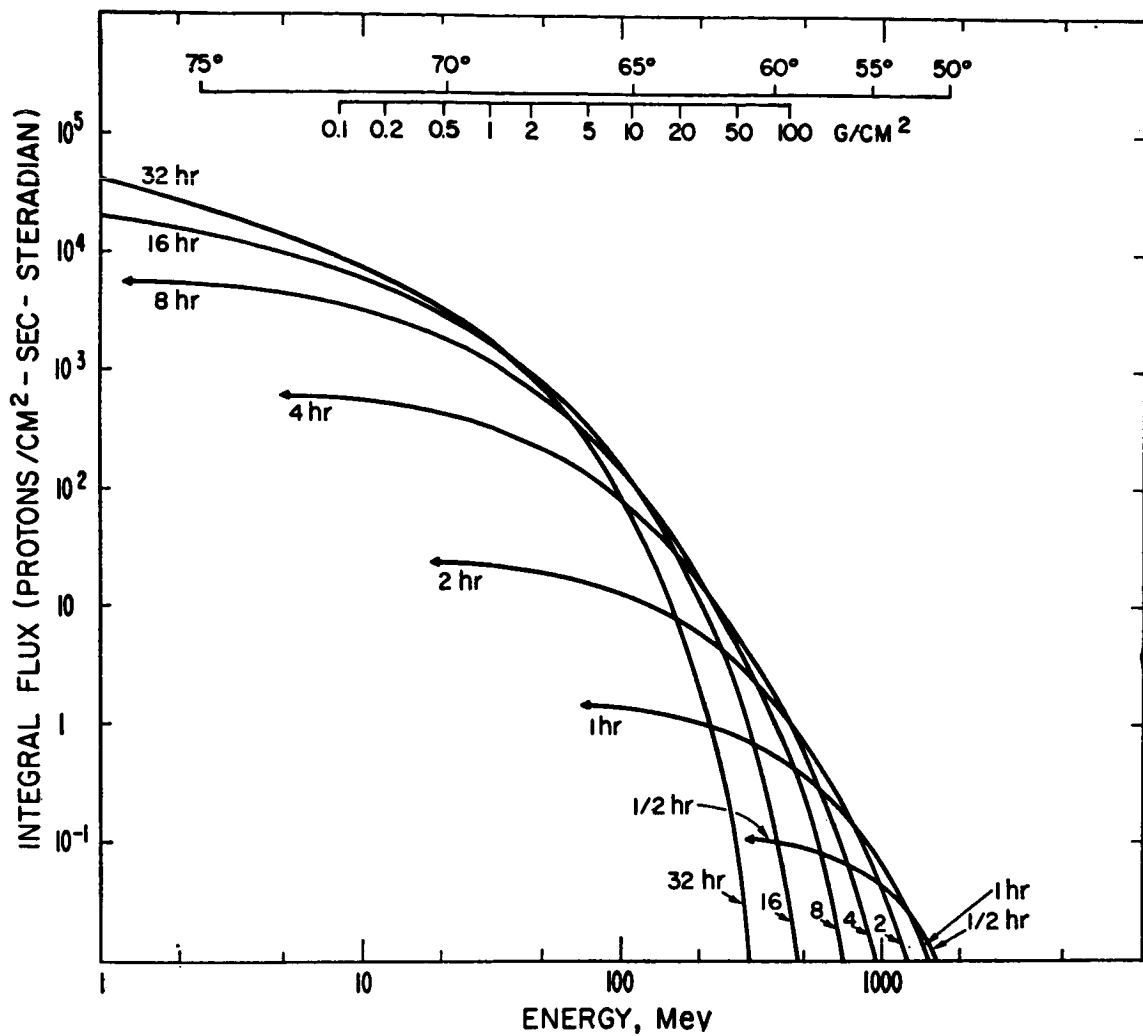
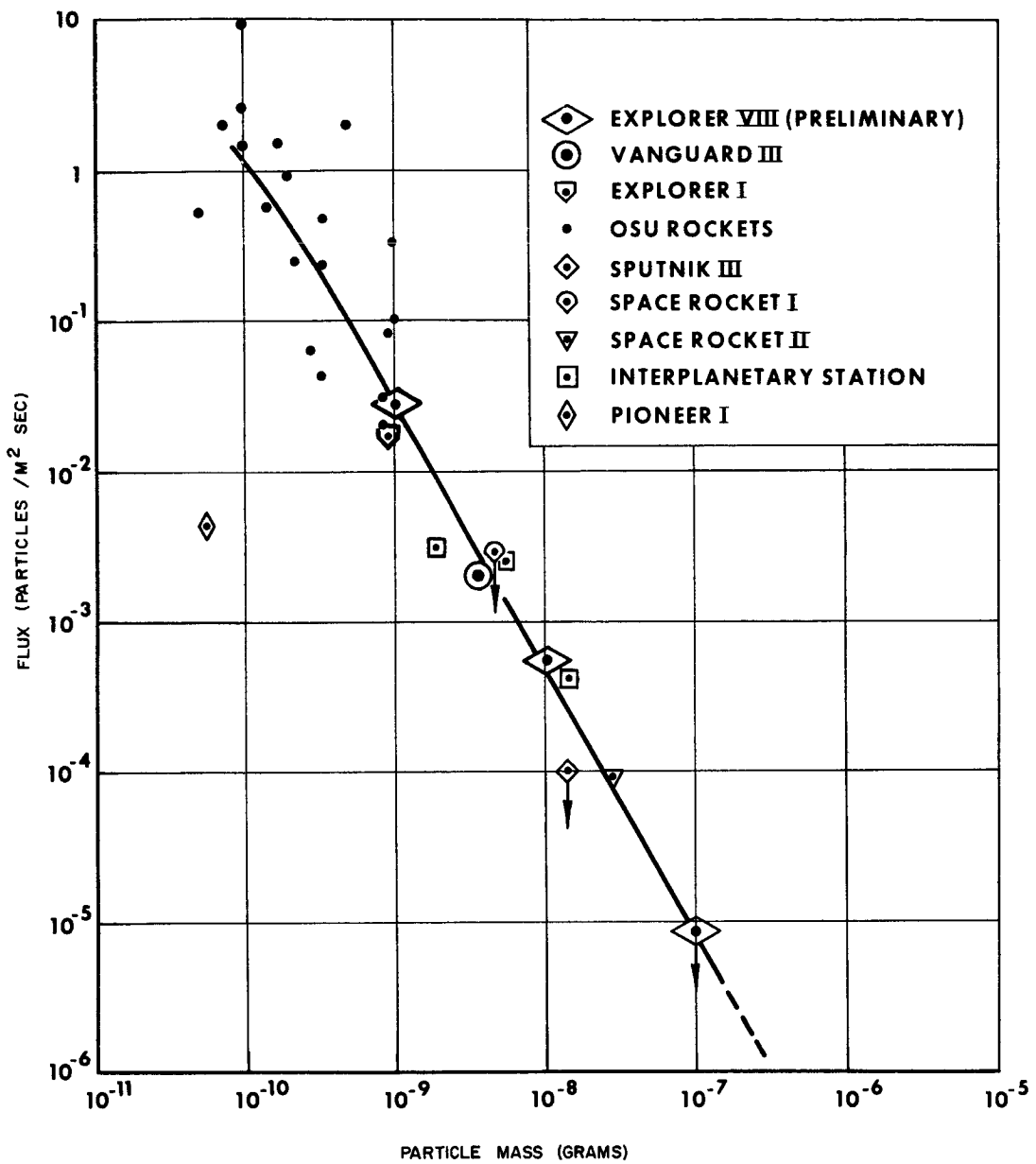


Figure 26



SPECTRA OF PARTICLES ARRIVING AT THE EARTH
AT VARIOUS TIMES FOLLOWING A SOLAR FLARE

Figure 27



MICROMETEOROID FLUX

Figure 28

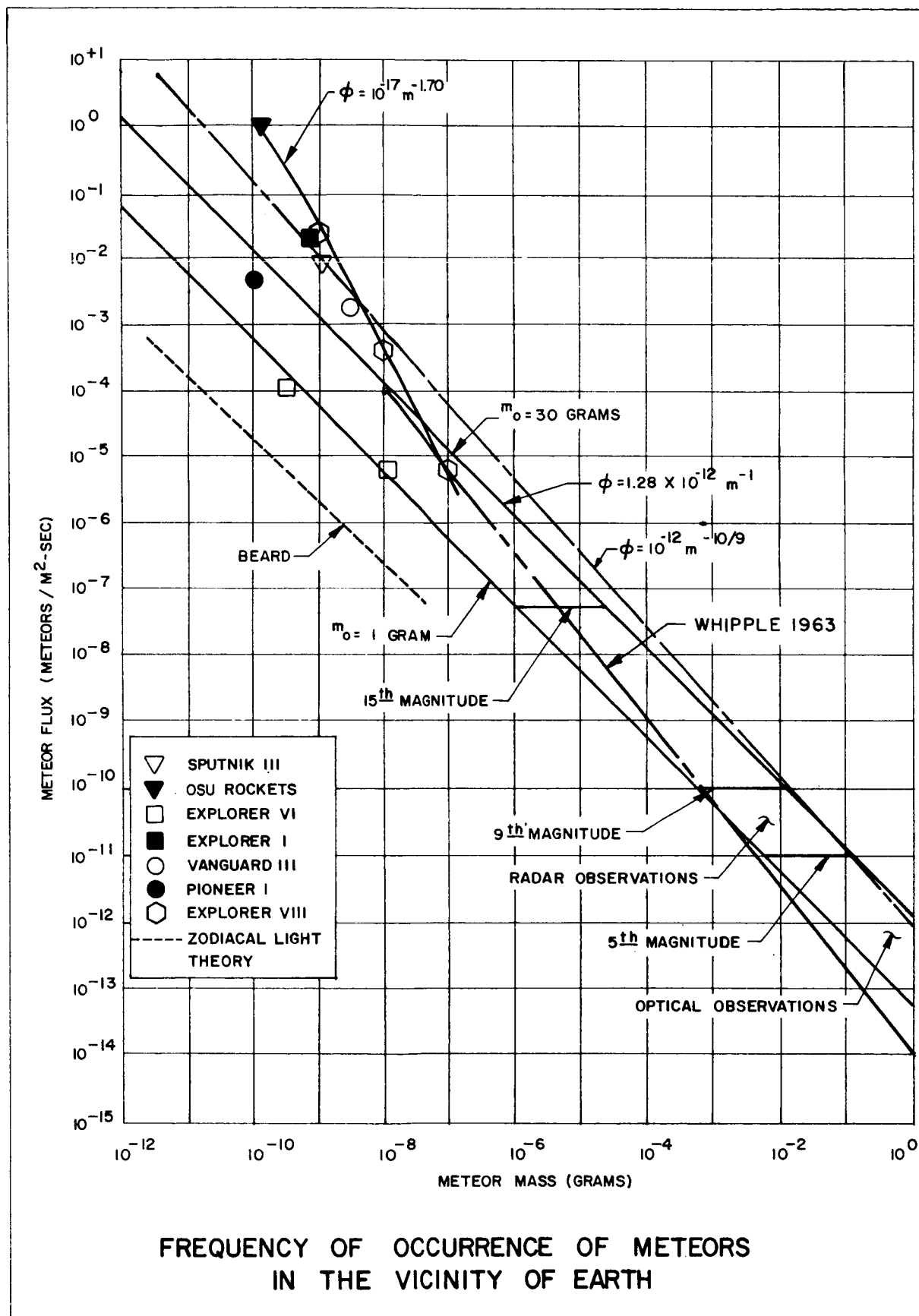
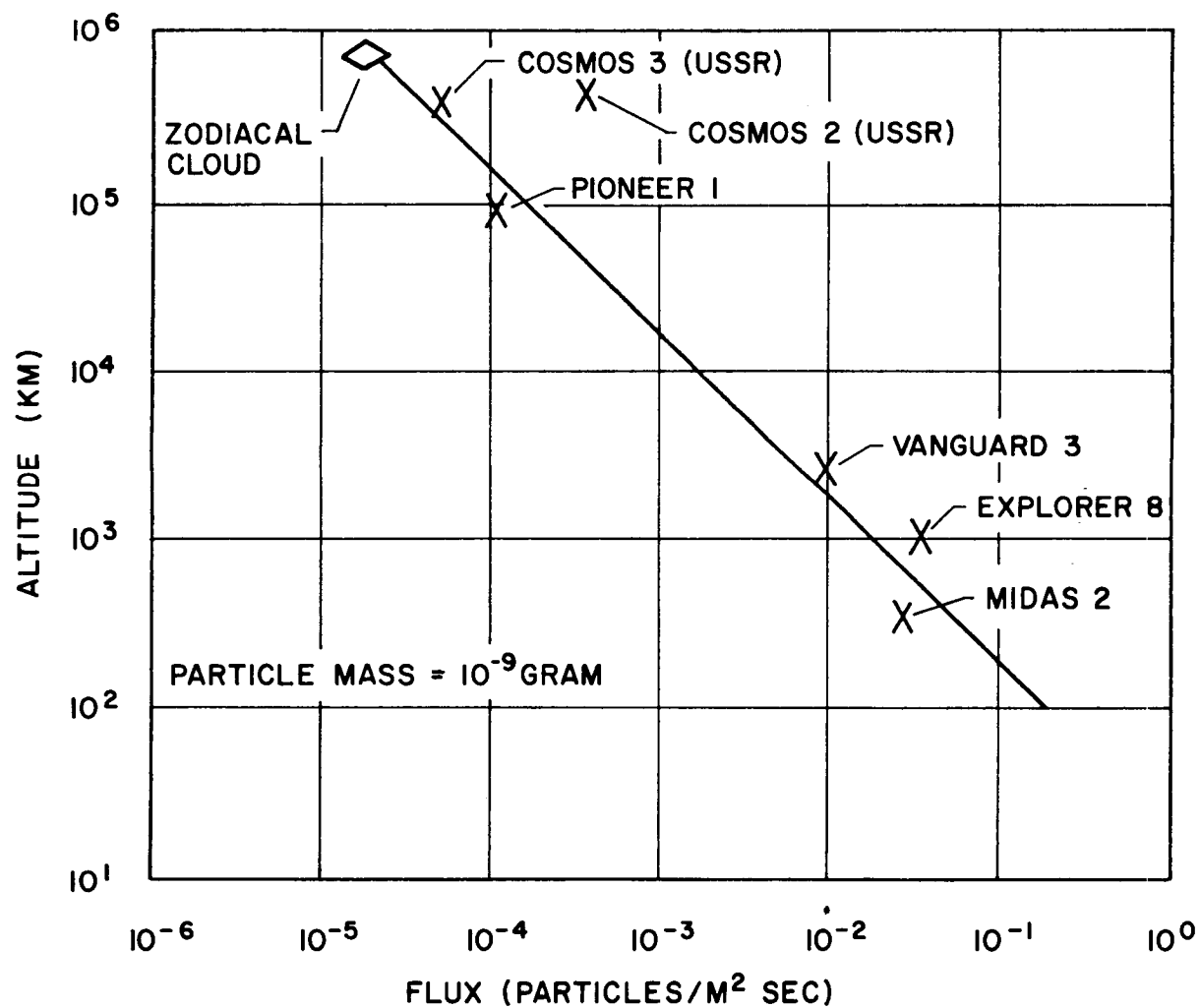


Figure 29



ALTITUDE - DEPENDENCE OF MICROMETEOROID FLUX

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